Capnography
A Monitoring Tool with Usual and Unusual Applications

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Capnography

- 1943 Luft developed 1st capnograph
  - Infra-red CO₂ measuring instrument
  - Capnography standard of care
    - Monitoring ventilated patients
Capnography

- CO₂ production
- Pulmonary perfusion
- Alveolar ventilation
- Airway disease
- Respiratory patterns
- Ventilatory failure
- Cardiac failure
- Ventilator problems
  - Rebreathing CO₂
  - Blockage/malplacement of ETT
  - Leaks breathing circuits
  - ETT cuff integrity
Capnography

- Infra-red spectrography
  - CO₂ absorbs specific wavelengths IR light
  - Amount absorbed $\propto$ concentration

- Interference
  - Atmospheric pressure
  - O₂
  - Water vapor
Capnography

- **Side-stream capnography**
  - CO₂ sensor in the main unit
  - Aspirates gas samples

- **Main-stream capnography**
  - CO₂ sensor in breathing circuit
Capnography

- **Time capnography**
  - CO$_2$ concentration over time

- **Volume capnography**
  - Accumulating CO$_2$ volume during expiration
  - Used in attempts to measure cardiac output
Capnography

- pH-sensitive chemical indicator filters
  - Changes color when exposed to CO$_2$
  - Response time changes breath-by-breath
  - Not sensitive to low CO$_2$
    - CPR, EXIT
Time Capnogram

- **Expiratory segment**
  - **Phase I (baseline)**
    - Anatomical/apparatus DS
  - **Phase II – upstroke**
    - Mixing DS gas/alveolar gas
  - **Phase III - plateau**
    - CO₂-rich gas from the alveoli
    - Always has a positive slope
      - Steady excretion of CO₂ into alveoli during expiration
      - As the alveoli volume decreases
      - Concentration CO₂ increases
    - Late emptying of alveoli - long time constants
      - Lower ventilation/perfusion ratios
      - Higher CO₂ concentrations
Time Capnogram

- **Inspiratory segment**
  - Phase 0
    - Rapid descent to the base line
    - Initial part of the horizontal base line
Time Capnography
Capnography

- Paco$_2$ is determined by
  - Pco$_2$ of all perfused alveoli
- ETCO$_2$ represents the
  - Pco$_2$ of all ventilated alveoli
- Paco$_2$ - ETCO$_2$ gradient
  - (a-ET)PCO$_2$
  - V/Q abnormalities
- Alveolar dead space ventilation
  - Volume of alveoli that are ventilated but not perfused
  - Failure of pulmonary perfusion
    - Secondary to decreased CO
    - Secondary increased pulmonary vascular resistance
Alveolar Dead Space

\[ (\text{aADV}) = \frac{\text{Paco}_2 - \text{PETCO}_2}{\text{Paco}_2} \]

\[ \text{PETCO}_2 = 40 \]

\[ \text{Paco}_2 = 42 \]

\[ \text{Paco}_2 - \text{PETCO}_2 = 20 \]
Capnography
Alveolar Dead Space

- (a-ET)PCO2 gradient
  - Index of alveolar dead space ventilation
  - Normally PETCO₂ < Pₐ₈C₀₂ by 2-5 mmHg
    - Vary depending on age/health of lungs
- Alveolar dead space (ADV)
  - Changes in ADV $\propto$ changes in (a-ET)PCO₂
  - (a-ET)PCO₂ estimate of V/Q mismatching
Capnography
Alveolar Dead Space

- (a-ET)PCO$_2$ gradient dependent on
  - ADV
- Temporal, spatial, and alveolar mixing defects
  - Factors that influence the slope of phase III
- Increased ADV ≠ increase (a-ET)PCO$_2$
  - If there is an associated increase slope phase III
Capnography
Slope Phase II & Phase III

- Prolonged, sloped upstroke (II), no plateau
  - Bronchospasm
  - Obstructive pulmonary disease
  - Kinked endotracheal tube
  - Leaks in breathing circuit

- Slope to plateau (III)
  - All cases
    - CO$_2$ excreted, alveoli progressively smaller
    - Range of V/Q ratios, variation of time constants
  - Can change regional V/Q
    - Changes in CO
    - Changes in airway resistance
  - Steep slope indicates abnormalities V/Q mismatch
    - If extreme – ETCO$_2$ > Paco$_2$
Capnography
Slope Phase III

![Image of capnography monitor with data]

![Graph of CO2 over time]

**Slope Phase III**

- SENSOR 02!
- %O2 SENSOR: %O2 = 100
- inCO2: 0
- RR: 11
- CO2mmHg: 66
- HR: 
- %SpO2
Normal

\[ \text{Paco}_2 \]
Increased ADV
\[ \text{PETCO}_2 > \text{Paco}_2 \]
Capnography
Negative (a-ET)PCO₂

- Large tidal volume/low frequency ventilation
  - Better ventilation of dependent well-perfused alveoli
  - Improves V/Q matching
  - Deep breaths
    - Alveoli with long time constants time to empty
      - Would have remained in the airways with small, rapid breaths
      - Low V/Q areas (higher PCO₂) make more contribution
        - at the end of the tidal expiration
      - End of phase III exceeds the mean PaCO₂
Capnography
Factors Causing Phase III Slope

- Late emptying alveoli - long time constants
  - Low V/Q – higher Pco₂
    - Alveolar mixing defect - incomplete gas mixing
    - Temporal mismatching
      - Max ventilation and max perfusion out of sequence
      - Perfusion is highest during the later expiration - ventilation is lowest
  - Regional variation in ventilation per unit perfusion
    - Spectrum of V/Q ratios
    - If asynchronous emptying
      - Long time constants – slope phase III
    - If synchronous emptying
      - Well mixed and little slope phase III
Clinical Uses of Capnography

- Noninvasive predictor of Paco$_2$
  - Decrease arterial gas sampling
- Nasal sampling
  - Spontaneous breathing
  - Healthy lungs
  - No intranasal oxygen
  - Good estimate PaCO$_2$
Clinical Uses of Capnography

- Ventilation
  - Continuous capnography
  - If normal respiratory/car diovascular physiology
    - Botulism foal
  - Continuous real time monitor adequate ventilation
    - $\text{PETCO}_2$ changes indicative of PaCO$_2$ changes
    - Relationship of $\text{PETCO}_2$/PaCO$_2$ established
    - Assume changes in PETCO$_2$ predict changes PaCO$_2$
Clinical Uses of Capnography

- Alveolar hypoventilation
  - Increases PaCO₂ \( \propto \) increase PETCO₂
- Confounding factors
  - (a-ET)PCO₂ difference
  - Simultaneous ABG/PETCO₂ values noted
- (a-ET)PCO₂
  - Indicator of V/Q mismatching - pulmonary disease
  - (a-ET)PCO₂ difference widens
    - Predict the severity/progression respiratory disease
Clinical Uses of Capnography

Ventilation

- Identify problems with the ventilatory circuit
  - Ventilated - no spontaneous breathing
    - PETCO$_2$ falls to zero instantaneously following circuit breaks
  - Ventilated - spontaneous breathing
    - Circuit disconnections towards the neonate – instant
    - Circuit disconnections towards the ventilator – slow
  - Early warning of CO2 retention - faulty ventilator connections

- Most common reason for the capnograph suddenly zero
  - Deflated endotracheal tube cuff
Clinical Uses of Capnography
Endotracheal Tube

- Confirm ETT placement
- Detect partial occlusion ETT
  - Secretions
  - Kinking tube
  - Distortions waveform
    - Prolonged phase II
    - Steeper phase III
    - Uneven height of waves
Clinical Uses of Capnography Monitor During Weaning

- ABG – pain/stress of sampling
- Capnography - evaluate PaCO₂ trend
- Monitor breathing pattern
- Monitor consistency of breathing
- Waveforms from spontaneous ventilation
  - Depth spontaneous breaths
  - Consistency of spontaneous ventilation
Clinical Uses of Capnography
Cardiac Output

- Decreased cardiac output/pulmonary blood flow
  - Decrease in PETCO₂
  - Increase in (a-ET)PCO₂
  - % decrease PETCO₂ \propto % decrease in CO
- Capnography ideal for monitoring cardiac output
  - CPR
  - EXIT
- As long as ventilation is constant
  - PETCO₂ is monitor of pulmonary blood flow
Clinical Uses of Capnography

CPR

- Cardiac arrest
  - No blood flow to lungs
  - $\text{PETCO}_2 = 0$

- Cardiac compressions
  - Low cardiac output
  - $\text{PETCO}_2 \ 6-12$
  - Very large ADV
Clinical Uses of Capnography
CPR

- **ROSC**
  - Cardiac output increasing
  - PETCO$_2$ > 18 and rising
  - ADV large but decreasing

- **PETCO$_2$ function of CO for any given ventilation**
  - Noninvasive monitor of pulmonary blood flow
  - Monitor the effectiveness of cardiopulmonary resuscitation
  - Determine the most effective technique of cardiac compression
  - PETCO$_2$ monitoring prognostic
  - If low > 10 minutes, cardiopulmonary resuscitation is futile
Clinical Uses of Capnography

- **EXutero Intrapartum Treatment**
  - Beginning birth resuscitation during Stage III
  - Intubation and ventilation in the canal

- **When ventilation is initiated**
  - PETCO₂ very low – fetal circulation

- **As lung is expanded by ventilation**
  - Blood flow redirected to the lungs
  - CO to lungs increases
  - PETCO₂ increases
Clinical Uses of Capnography

- **PETCO₂ stays low or 0**
  - CO compromised
- **PETCO₂ > 40**
  - Viable
  - Should continue to increase/stabilize
- **PETCO₂ 10 – 20**
  - Significant compromise
  - Rx IT epinephrine
- **Caveats**
  - Low PETCO₂ from hyperventilation
    - Operator error
  - Ventilation may cause cardiac pump
    - PETCO₂ 10-14
    - Nonviable foal
Clinical Uses of Capnography
Progress of Pulmonary Disease

- Monitored by serial (a-ET)PCO₂
- Improved (a-ET)PCO₂ gradient
  - As the pulmonary disease improves
- Shape of capnogram
  - Increased V/Q mismatch
    - Increase slope of phase III
  - Airway disease
    - Various time constants
    - Prolonged phase II
    - Steeper phase III
- Airway disease improves with therapy
  - Capnogram reverts to normal as V/Q ratios normalize
Clinical Examples
Capnography
No Plateau
Capnography
Wave Variation
Capnography
Curare Notch
Uneven V/Q
CAPNOGRAPHY:
A MONITORING TOOL WITH USUAL AND UNUSUAL APPLICATIONS
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The first infra-red CO₂ measuring instrument was introduced in 1943 by Luft. Since then capnography has become an integral part of monitoring respiratory status of ventilated intensive care patients. Despite this, much of the information capnography conveys goes unrecognized. Beyond a simple estimate of PaCO₂, capnography provides information about CO₂ production, pulmonary perfusion, alveolar ventilation, respiratory patterns, and elimination of CO₂ from the ventilator. Life-threatening conditions such as blockage or malplacement of the endotracheal tube, sudden ventilatory failure, cardiac failure or the presence of defective breathing circuits can be quickly identified with capnography.

Most clinical capnography utilizes infra-red spectrographs. Carbon dioxide selectively absorbs specific wavelengths of infra-red light. The amount of light absorbed is proportional to the concentration of the absorbing molecules, so the concentration of a gas can be determined by comparing the measured absorbance with the absorbance of a known standard. Interfering substances include oxygen and water vapor. In large animal neonatology, side-stream capnography (CO₂ sensor located in the main unit and a tiny pump aspirates gas samples for measurement) is more practical than main-stream capnography (CO₂ sensor inserted between the breathing circuit and the endotracheal tube). Time capnography, which graphs the CO₂ concentration in the respiratory gas throughout the respiratory cycle, is commonly utilized. Volume capnography which graphs the accumulating CO₂ volume during expiration, has only been used experimentally in attempts to measure cardiac output.

In certain circumstances the use of pH-sensitive chemical indicator filters can be useful for CO₂ detection. The pH-sensitive chemical indicator filter in a plastic housing is connected between the endotracheal tube and the breathing circuit. The filter changes color when exposed to CO₂. The color varies between expiration and inspiration, as CO₂ levels change. The color varies from purple (when exposed to room air or oxygen) to yellow (when exposed to 4% CO₂). The response time is fast enough to detect changes of CO₂ breath-by-breath but is not very sensitive when CO₂ output is low as is during CPR. It can be used during EXIT but as the fetus becomes less viable, as with CPR, it may not be sensitive enough to adequately replace a capnograph.

The time capnogram can be considered as having an expiratory segment and an inspiratory segment. The expiratory segment can be divided into three phases. Phase I (baseline) represents the CO₂-free gas from the airways (anatomical and apparatus dead space). Phase II is the upstroke of the curve due to mixing of dead space gas with alveolar gas. Phase III is the plateau with CO₂-rich gas from the alveoli. Phase III almost always has a positive slope, indicating a rising PaCO₂. There are several reasons for this upstroke. First there is steady excretion of CO₂ into the alveoli even during expiration and as the alveoli volume decreases, the concentration of CO₂ during expiration increases. Second, late emptying of alveoli with long time constants have lower ventilation/perfusion ratios and, thus higher C0₂ concentrations. The expiratory segment of the curve, referred to as Phase 0, begins as an almost right angle turn and rapidly descent to the base line. It continues as the initial part of the horizontal base line until expiration begins once more.

Using Fick's Principle, attempts have been made to determine cardiac output non-invasively implementing periods of CO₂ rebreathing during which CO₂ partial pressure of mixed venous blood is obtained and the exponential rise of the PETCO₂ value measured. The results are encouraging in patients with healthy lungs, but controversial when the lungs are diseased.

The gradient between arterial and PETCO₂ is a useful index of alveolar dead space ventilation. Usually the PETCO₂ is lower than PaCO₂ by 2-5 mmHg. The (a-ET)PCO₂ gradient is due to the V/Q mismatch (alveolar dead space) as a result of temporal, spatial, and alveolar mixing defects. The (a-ET)PCO₂ / PaCO₂ fraction is a measure of alveolar dead space, and changes in alveolar dead space correlate well with changes in (a-ET)PCO₂.
An increase in (a-ET)PCO2 suggests an increase in dead space ventilation. Hence (a-ET)PCO2 is an indirect estimate of V/Q mismatching of the lung.

Arterial and PETCO2 gradient does not always reflect alveolar dead space. The (a-ET)PCO2 gradient is dependent on alveolar dead space and factors that influence the slope of phase III. So, an increase in the alveolar dead space may not be associated with an increase in the (a-ET)PCO2 if there is an associated increase in the slope of the phase III.

Negative (a-ET)PC02 values may occur for several reasons. Large tidal volume and low frequency ventilation result in better ventilation of dependent well-perfused alveoli which improves V/Q matching. With deep breaths, gas from alveoli with long time constants has time to empty, whereas it would have remained in the airways with small frequent rapid breaths. The low V/Q areas (alveoli with higher PCO2) make more contribution to the PETCO2, as it arrives at the end of the tidal expiration. So the end of phase III exceeds the mean PaC02, resulting in negative (a-ET)PCO2.

There are many other clinical uses of capnography. It is a simple, noninvasive predictor of PaCO2, helping to avoid arterial gas sampling in selective instances. When nasal sampling is utilized in spontaneous breathing foals with healthy lungs without the use of intranasal oxygen, it provides a good estimate of PaCO2. The (a-ET)PCO2 gradient can vary depending on age and health of the lungs. Alveolar hypoventilation increases PaCO2 as well as PETCO2, making it an accurate reflection of changes in arterial values. But several factors can affect the (a-ET)PCO2 difference and thus decrease the predictability of PaCO2 from PETCO2. Whenever an arterial blood gas is obtained, the simultaneous PETCO2 should be noted so that (a-ET)PCO2 can be assessed. The (a-ET)PCO2 is an indicator of V/Q mismatching resulting from pulmonary disease. In neonates with respiratory disease, the (a-ET)PCO2 difference widens and the gradient can help predict the severity of the respiratory disease.

Every ventilated neonate should have continuous capnography. In ventilated neonates with normal respiratory and cardiovascular physiology, such as the ventilated botulism foal, PETCO2 values approximate PaCO2 values and serve as a continuous real time monitor of adequacy of ventilation. In these cases, changes in PETCO2 can often be regarded as indicative of changes in PaCO2. A number of factors affect the relationship of PETCO2 to PaCO2. In these cases with normal pulmonary function once the relationship of PETCO2 to PaCO2 is established by blood gas analysis, changes in PaCO2 may be assumed to occur in parallel with those in PETCO2.

Capnography can identify problems with the ventilatory circuit instantaneously before O2 and CO2 levels change in the blood. In ventilated neonates with no spontaneous breathing, PETCO2 falls to zero instantaneously following the disconnections in the circuit. However, in ventilated neonates breathing spontaneously, circuit disconnections distal to CO2 sampling site (towards the neonate) can be identified as CO2 concentration falls to zero, whereas, circuit disconnection proximal to the sampling site may not be detected as rapidly as PETCO2 values depends on the adequacy of spontaneous breathing. If spontaneous breathing is adequate, the PETCO2 values remain normal, whereas, PETCO2 values may rise gradually if spontaneous breathing is inadequate. Capnography is also useful in giving an early warning of CO2 retention caused by faulty ventilators and misconnections. The most common reason for the capnograph suddenly dropping to zero in our practice is a deflated endotracheal tube cuff.

In addition to confirming endotracheal tube placement in the trachea, capnography can detect partial occlusion of the endotracheal tube with secretions or kinking of the tube. Ventilation through partially kinked or obstructed tube produces distortions in CO2 waveform (prolonged phase II and steeper phase III) and uneven height of the CO2 tracings.
Capnography can be used to monitor alveolar ventilation during weaning from mechanical ventilation. Using an arterial blood gas alone may not be an adequate guide to decide on weaning because occasionally pain from blood sampling or stress from restraint will cause foals to hyperventilate and thus decrease the PCO2 level in the blood, which may not be a true indicator of the foal’s ventilatory status. Capnography can be used to evaluate the trend of PaCO2, breathing pattern, and importantly the consistency of breathing before extubation. Evaluation of CO2 waveforms produced by spontaneous ventilation during weaning gives information about the depth and consistency of spontaneous ventilation.

Reduction in cardiac output and pulmonary blood flow result in a decrease in PETCO2 (end tidal Pco2) and an increase in (a-ET)PCO2 (the gradient between arterial and end tidal Pco2). The percent decrease in PETCO2 directly correlates with the percent decrease in cardiac output. This makes capnography ideal for use during CPR and during EXIT for monitoring cardiac output. Increases in cardiac output and pulmonary blood flow result in better perfusion of the alveoli and a rise in PETCO2. Consequently alveolar dead space is reduced as is (a-ET)PCO2. As long as lung ventilation is constant (a very important criteria), PETCO2 monitoring can be used as a monitor of pulmonary blood flow.

Capnography is a valuable aid in monitoring cardiac output during CPR and EXIT. Any reduction in the cardiac output decreasing pulmonary blood flow produces increased alveolar dead space ventilation resulting in lower PETCO2 and an increased (a-ET)PCO2 gradient. During CPR or EXIT, as pulmonary blood flow increases, the PETCO2 increases as alveolar dead space decreases and the (a-ET)PCO2 gradient becomes smaller. PETCO2 is a function of cardiac output for any given ventilation making PETCO2 a noninvasive monitor of pulmonary blood flow. PETCO2 monitoring can be used to monitor the effectiveness of cardiopulmonary resuscitation. During cardiac arrest, circulation ceases and as long as ventilation continues, PETCO2 gradually disappears, reappearing only when circulation is restored either by effective cardiac compressions or return of spontaneous cardiac output. PETCO2 can be used to determine the most effective technique of cardiac compression for the individual and insure that cardiac output is present. PETCO2 monitoring may have a prognostic and if it remains minimal for greater than 10 minutes, cardiopulmonary resuscitation is futile.

Monitoring PETCO2 is also very valuable when performing EXIT (EXutero Intrapartum Treatment). EXIT is a technique for beginning birth resuscitation while the foal is still in the birth canal during a dystocia. The mainstay of EXIT is intubation and ventilation of the fetus while it is still in the canal. When ventilation is initiated the PETCO2 will be very low as the fetal lung receives little cardiac output. As the lung is expanded by ventilation, blood is redirected away from the placenta and to the lungs. As pulmonary cardiac output increases, so will the PETCO2. If it doesn’t, it means that cardiac output is compromised. During the EXIT procedure, PETCO2 monitoring is vital in directing therapy and predicting vitality.

Progress of pulmonary disease can be monitored by improved serial (a-ET)PCO2. As the pulmonary disease improves the initial abnormal (a-ET)PCO2 gradient will progressively improve as V/Q ratio normalizes. The shape of capnogram also gives information about V/Q status of the lung. Increased V/Q mismatch is suggested by an increase in the slope of phase III. In the presence of abnormal V/Q ratios in lungs, for example during bronchospasm, the emptying pattern of alveoli with various time constants produces a characteristic capnogram with prolonged phase II and a steeper phase III. As bronchospasm improves with therapy, the capnogram reverts to normal as V/Q ratios normalize.

Studying the shape of the capnogram will reveal information about the pathophysiology of lung disease. As was just mentioned, in severe airway obstruction the shape of the capnogram can be altered, with a prolongation or slanting of phase II and increased slope of phase III, the expiratory plateau. Bronchospasm, small airway disease, emphysema and obstructed endotracheal tube can all produce a slanted and prolonged phase 2 and increased slope of phase 3.
Capnography is a very useful monitoring technique in a number of critical care settings common in equine neonatal intensive care. A full understanding of capnography will greatly enhance its usefulness in these settings.