Capnography
A Monitoring Tool with Usual and Unusual Applications

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Caprnography.com
By BS Kodali, MD

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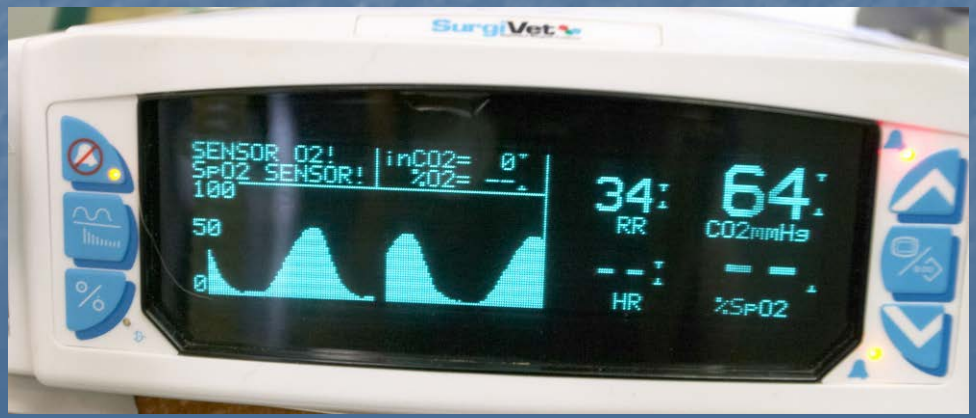
Capnography

- 1943 Luft developed 1st capnograph
  - Infra-red CO_2 measuring instrument
  - Capnography standard of care
    - Monitoring ventilated patients

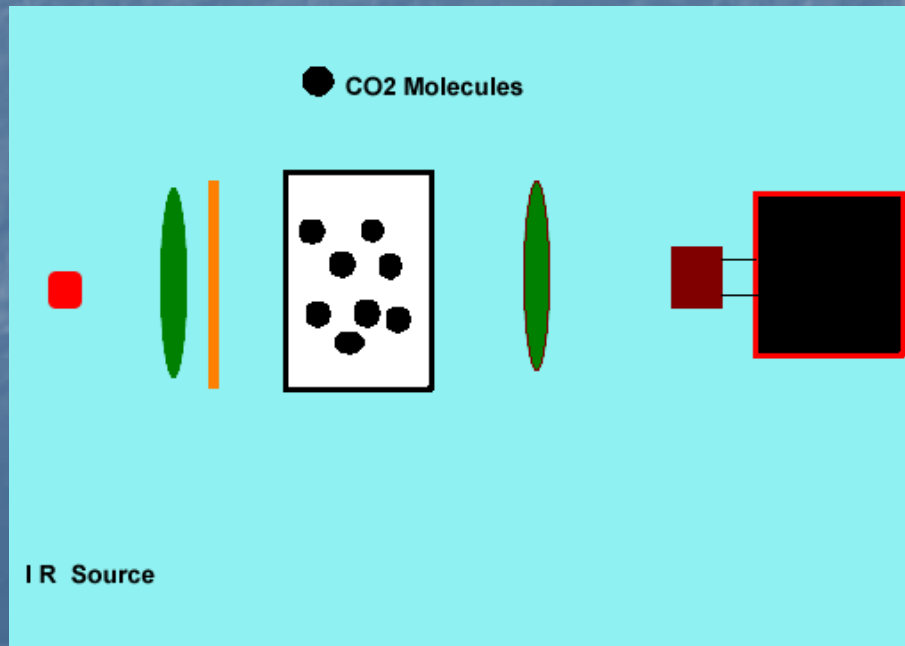


Capnography

- CO_2 production
- Pulmonary perfusion
- Alveolar ventilation
- Airway disease
- Respiratory patterns
- Ventilatory failure
- Cardiac failure
- Ventilator problems
  - Rebreathing CO_2
  - Blockage/malplacement of ETT
  - Leaks breathing circuits
  - ETT cuff integrity

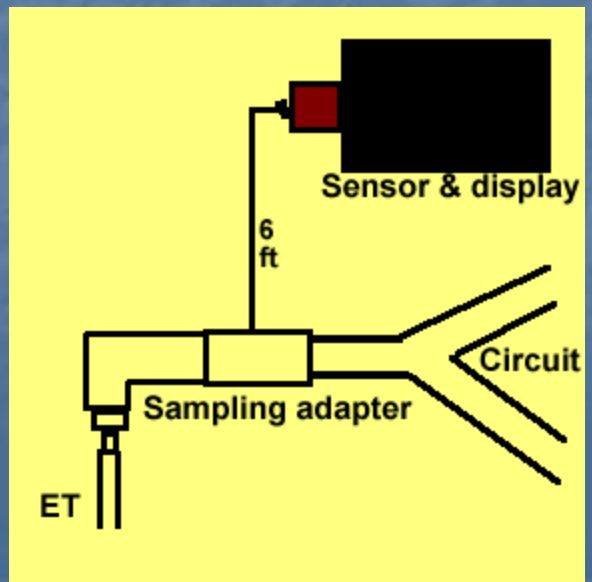
Capnography

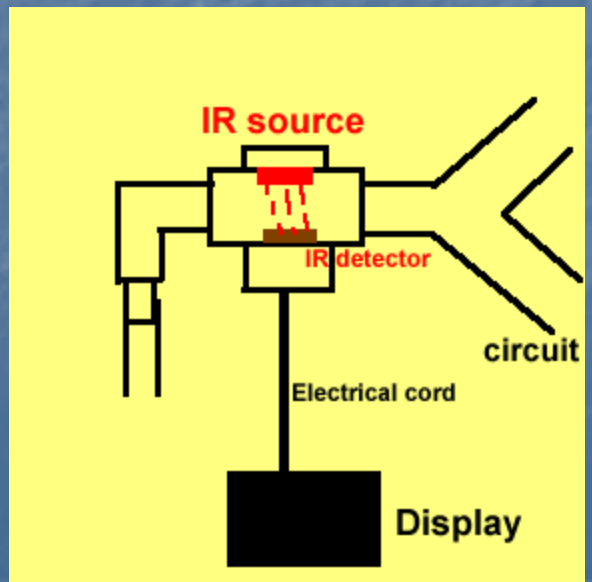
- Infra-red spectrography
  - CO_2 absorbs specific wavelengths IR light
  - Amount absorbed $\propto$ concentration
- Interference
  - Atmospheric pressure
  - O_2
  - Water vapor



Capnography

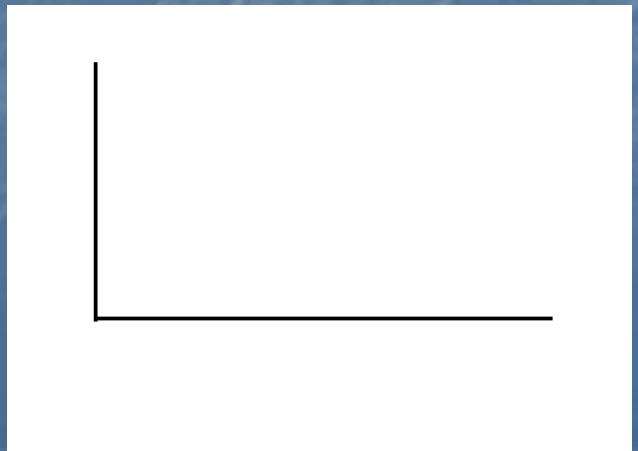
- Side-stream capnography
  - CO_2 sensor in the main unit
  - Aspirates gas samples
- Main-stream capnography
  - CO_2 sensor in breathing circuit

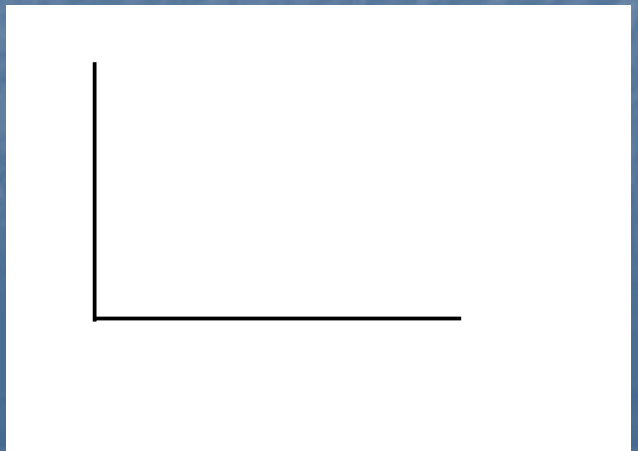




Capnography

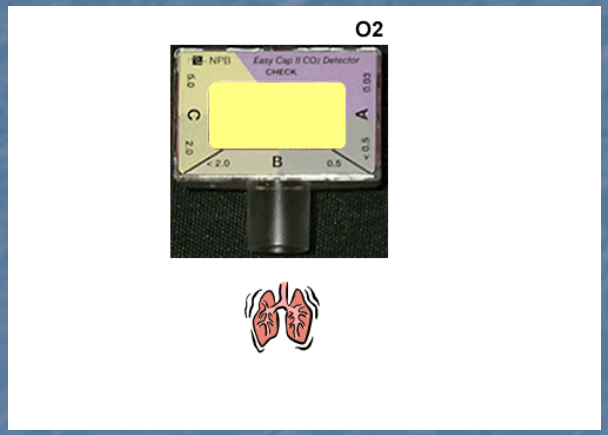
- Time capnography
  - CO_2 concentration over time
- Volume capnography
  - Accumulating CO_2 volume during expiration
  - Used in attempts to measure cardiac output

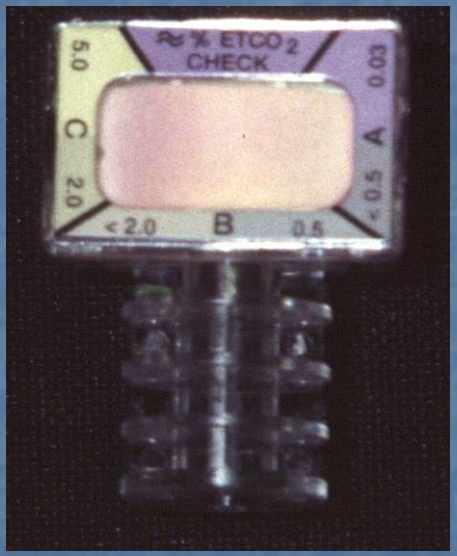




Capnography

- pH-sensitive chemical indicator filters
  - Changes color when exposed to CO_2

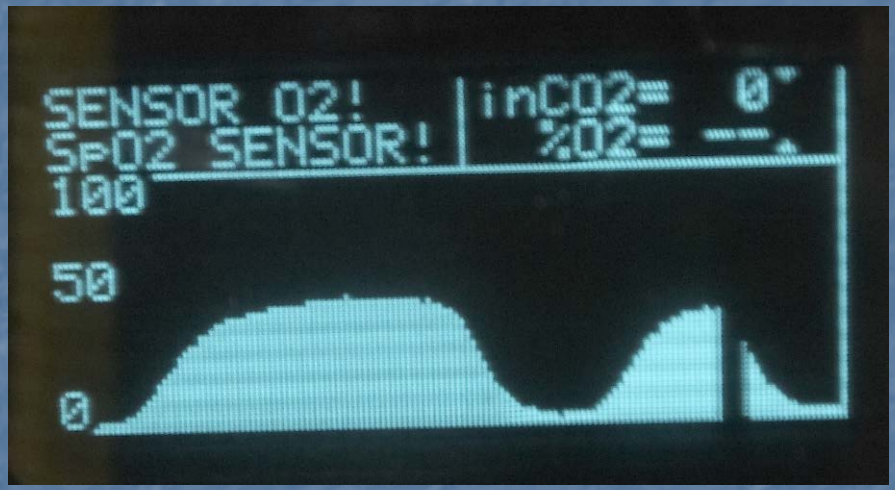




  - Response time changes breath-by breath
  - Not sensitive to low CO_2
    - CPR, EXIT

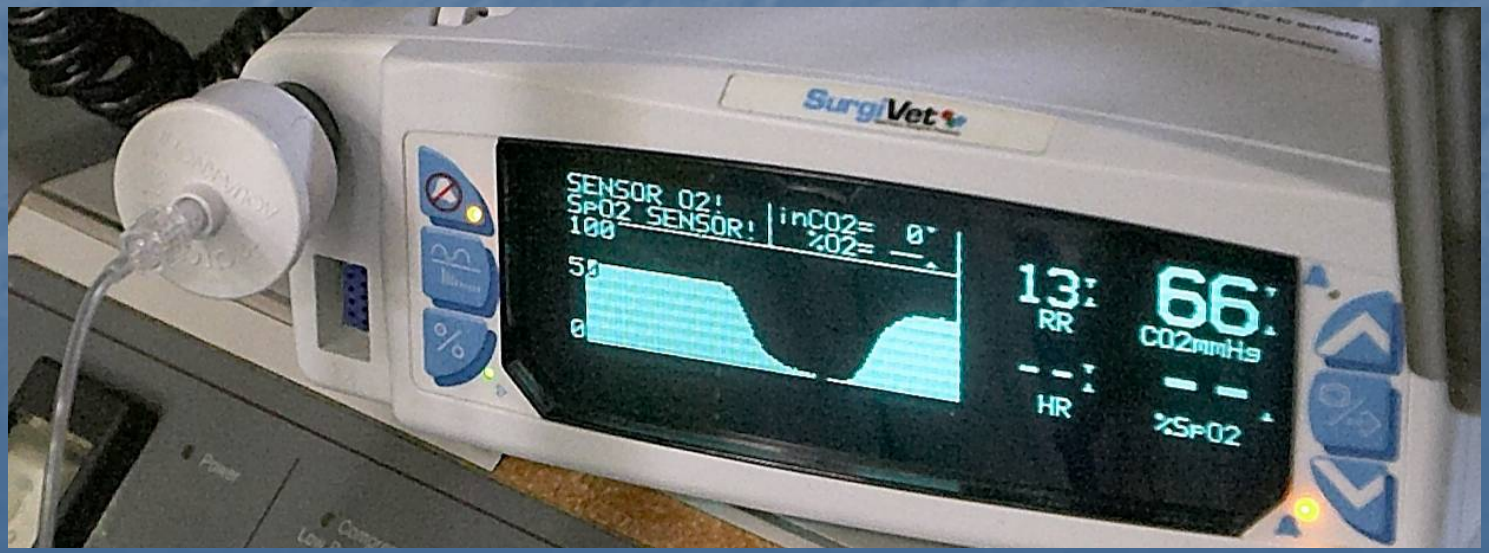
Time Capnogram

- Expiratory segment
  - Phase I (baseline)
    - Anatomical/apparatus DS
  - Phase II – upstroke
    - Mixing DS gas/alveolar gas
  - Phase III- plateau
    - CO_2-rich gas from the alveoli
    - Always has a positive slope
      - Steady excretion of CO_2 into alveoli during expiration
        - As the alveoli volume decreases
        - Concentration CO_2 increases
      - Late emptying of alveoli - long time constants
        - Lower ventilation/perfusion ratios
        - Higher $C0_2$ concentrations

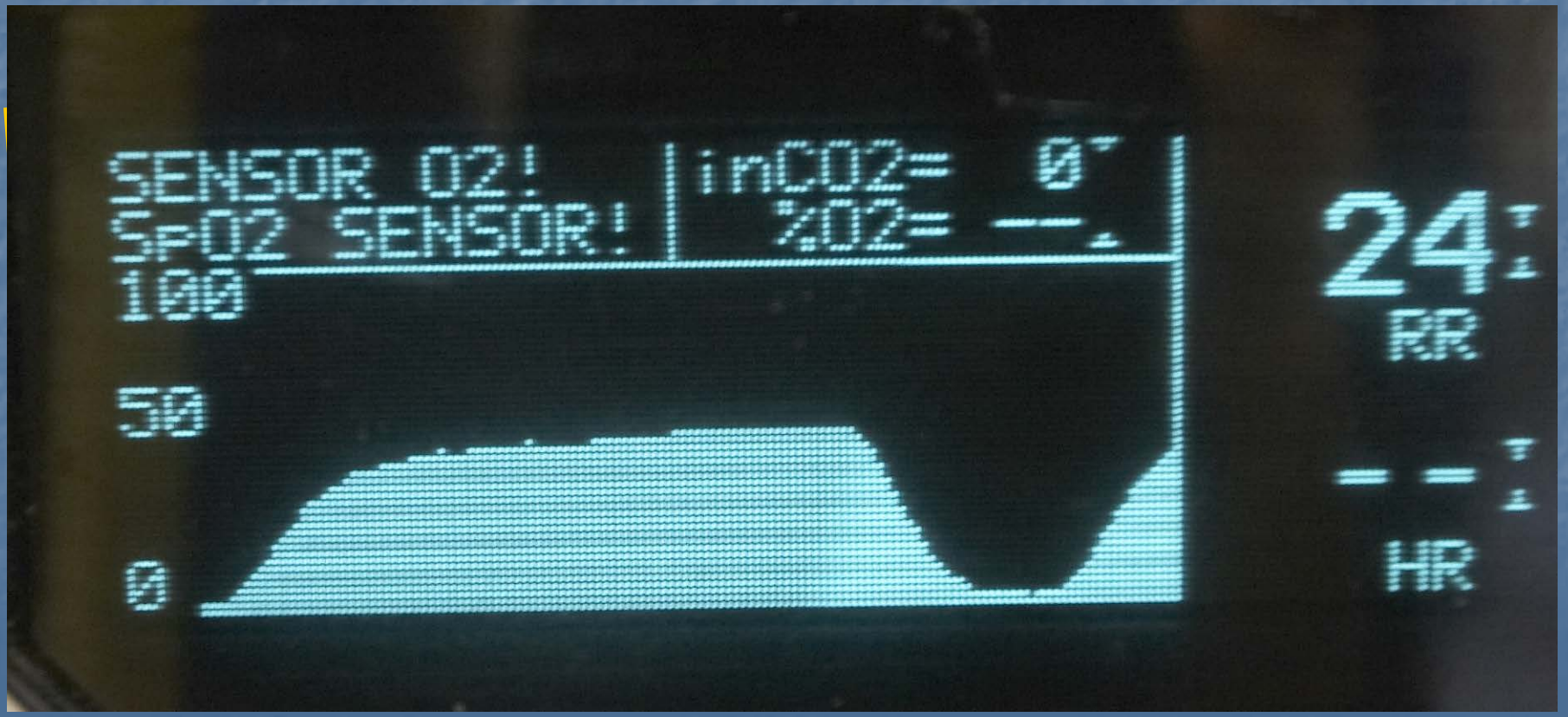


Time Capnogram

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



Time Capnography



Capnography

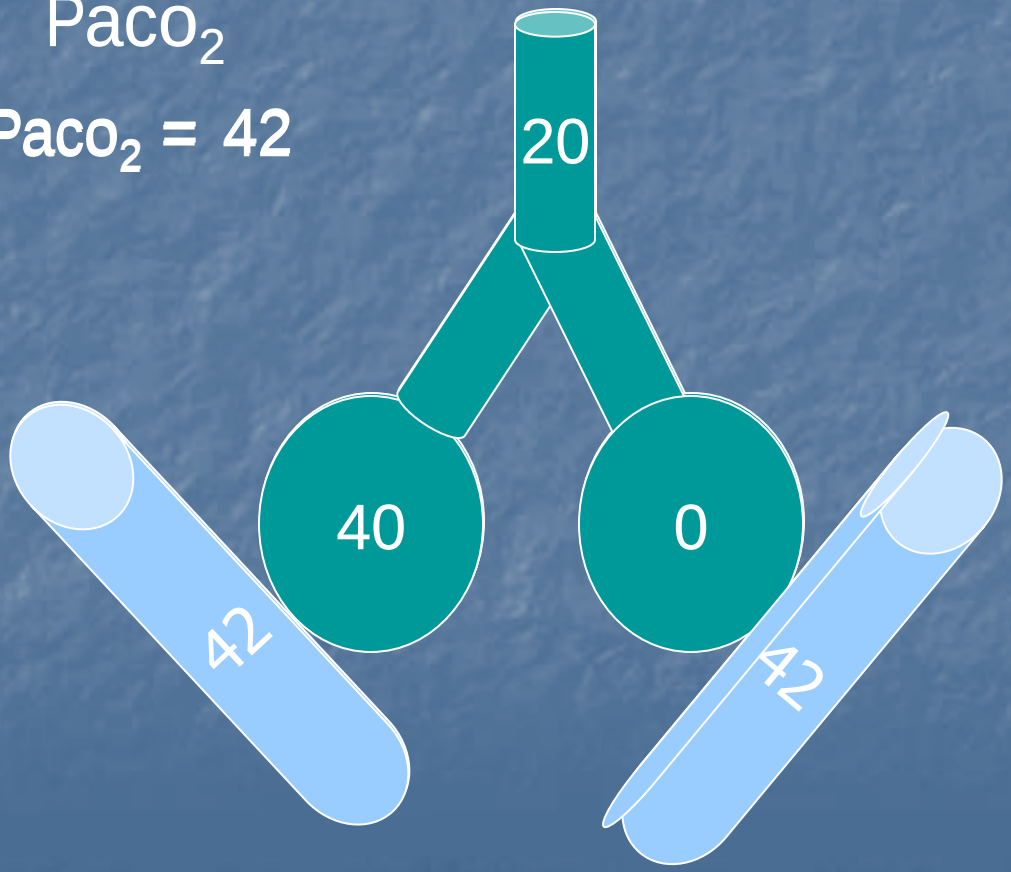
- $Paco_2$ is determined by
  - Pco_2 of all perfused alveoli
- $ETCO_2$ represents the
  - Pco_2 of all ventilated alveoli
- $Paco_2$ - $ETCO_2$ gradient
  - (a-ET)PCO_2
  - V/Q abnormalities
- Alveolar dead space ventilation
  - Volume of alveoli that are ventilated but not perfused
  - Failure of pulmonary perfusion
    - Secondary to decreased CO
    - Secondary increased pulmonary vascular resistance

Alveolar Dead Space

$PETCO_2 = 40$

$$\frac{Paco_2 - PETCO_2}{Paco_2}$$

$Paco_2 = 42$



Capnography
Alveolar Dead Space

- (a-ET)PCO2 gradient
  - Index of alveolar dead space ventilation
  - Normally $PETCO_2 < P_{aco_2}$ by 2-5 mmHg
    - Vary depending on age/health of lungs
- Alveolar dead space (ADV)
  - Changes in ADV $\propto$ changes in (a-ET)PCO_2
  - (a-ET)PCO_2 estimate of V/Q mismatching

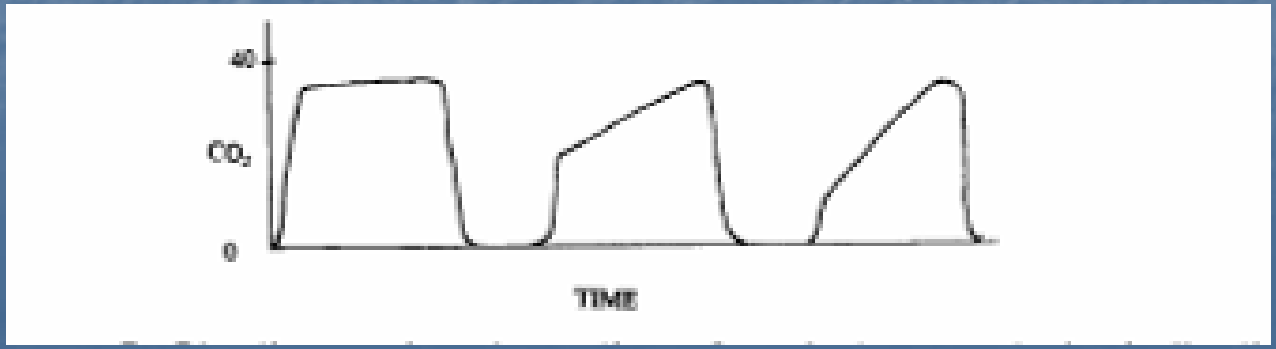
Capnography
Alveolar Dead Space

- (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

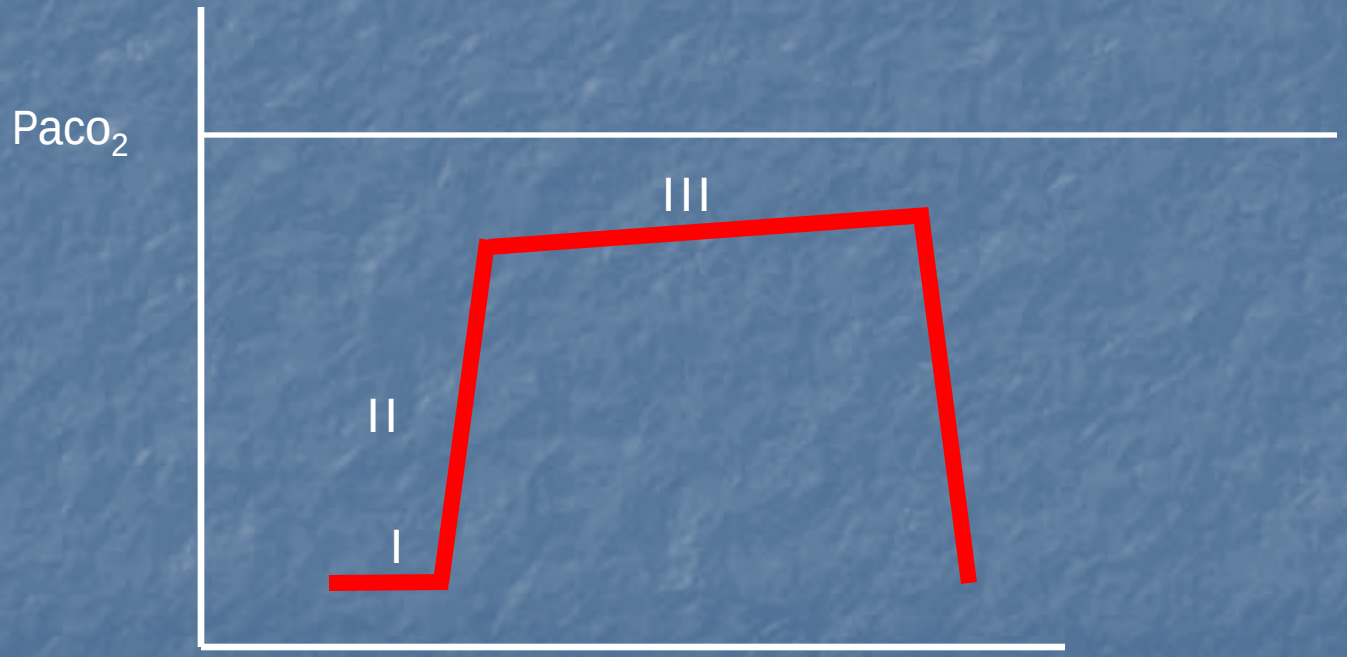
Capnography
Slope Phase II & Phase III

- 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 – $ETCO_2 > Paco_2$

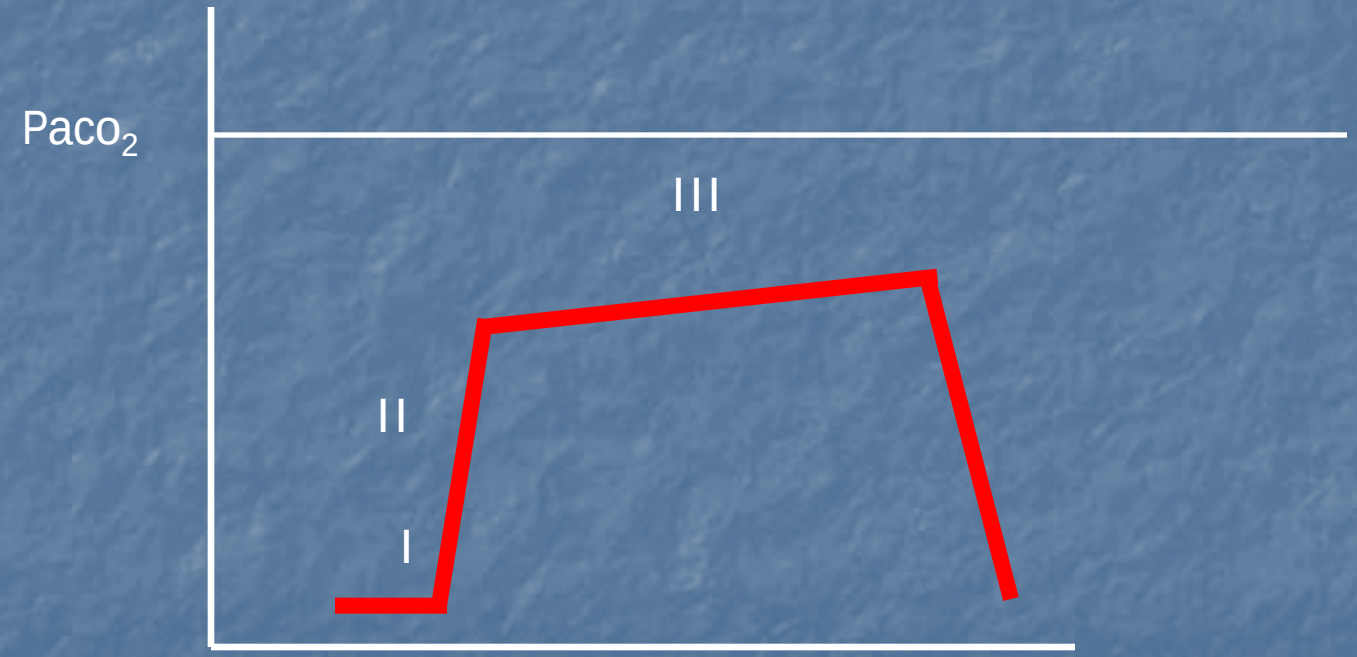
Capnography
Slope Phase III



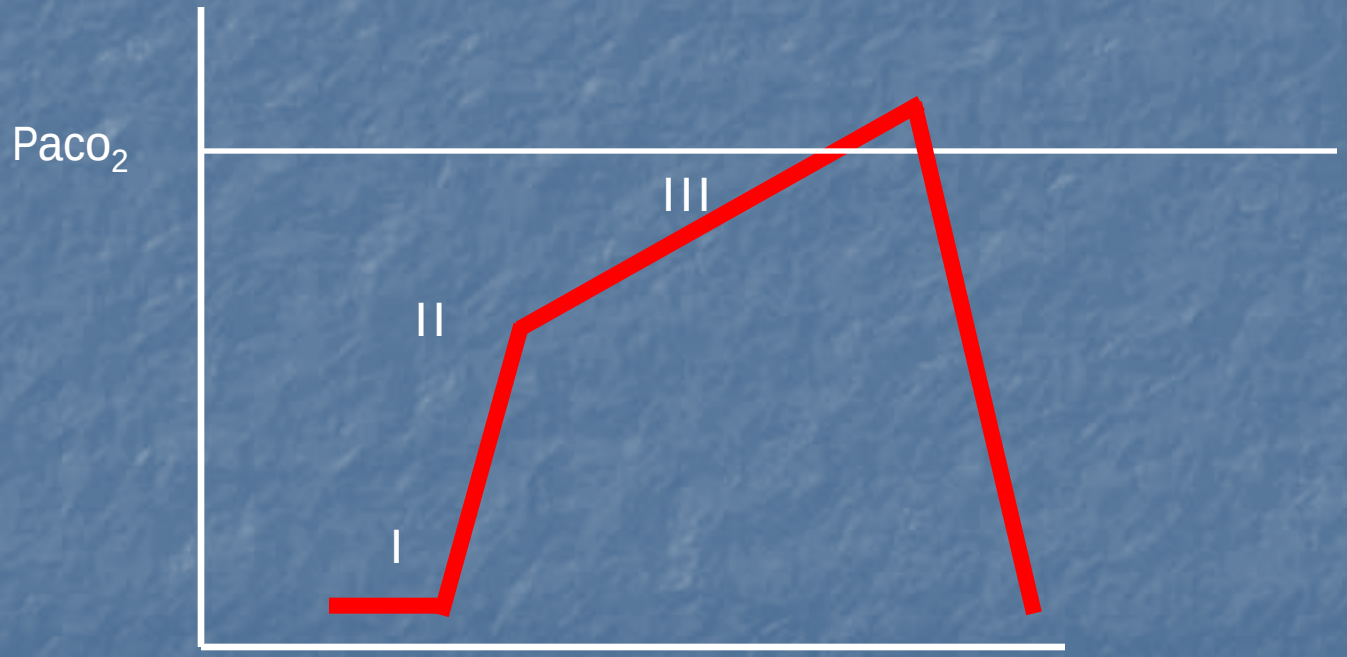
Normal



Increased ADV



$PETCO_2 > Paco_2$

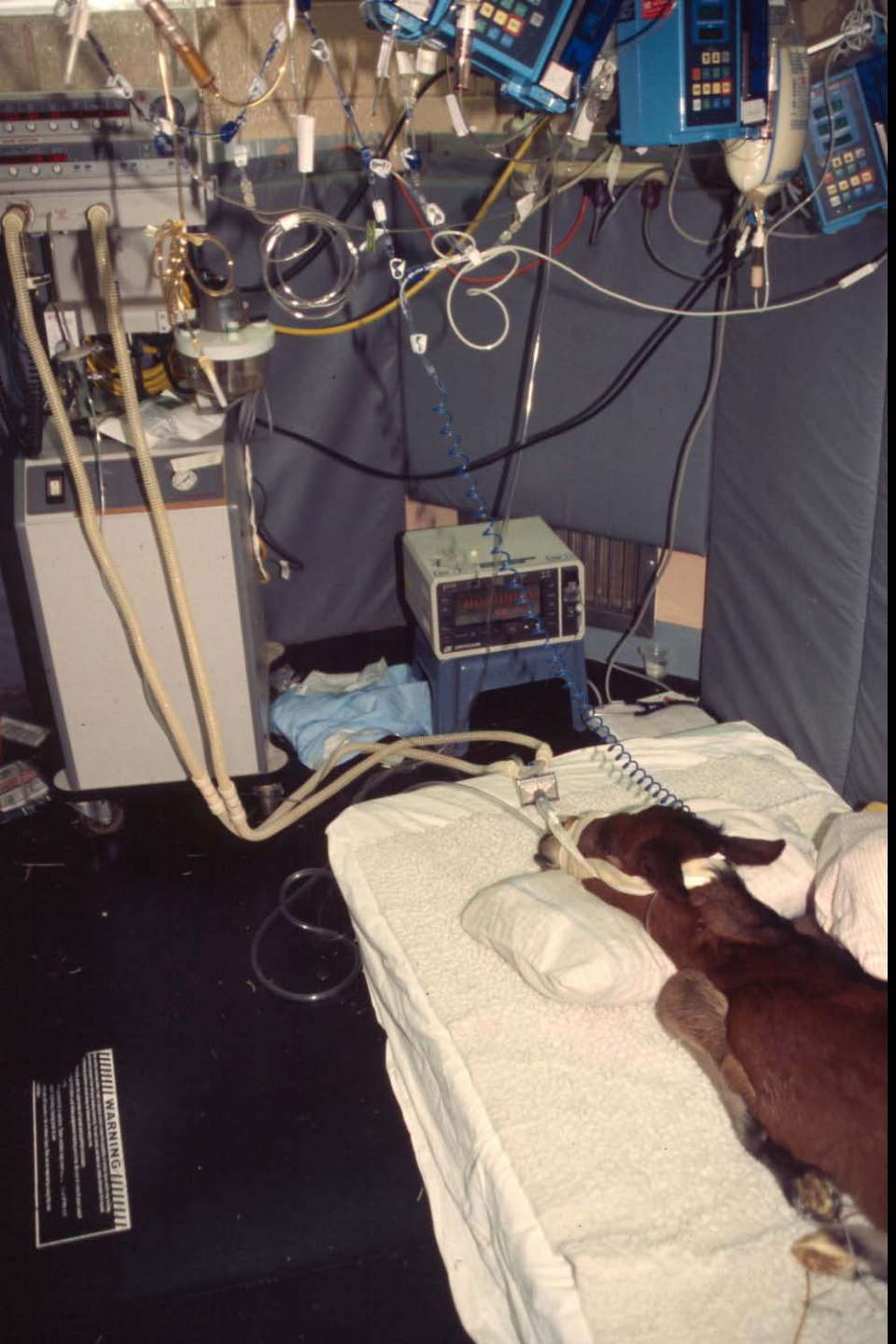


Capnography
Negative (a-ET)$PC0_2$

- 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 $PC0_2$) make more contribution
        - at the end of the tidal expiration
      - End of phase III exceeds the mean $PaC0_2$

Capnography
Factors Causing Phase III Slope

- Late emptying alveoli - long time constants
  - Low V/Q – higher Pco_2
    - 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


WARNING

Clinical Uses of Capnography

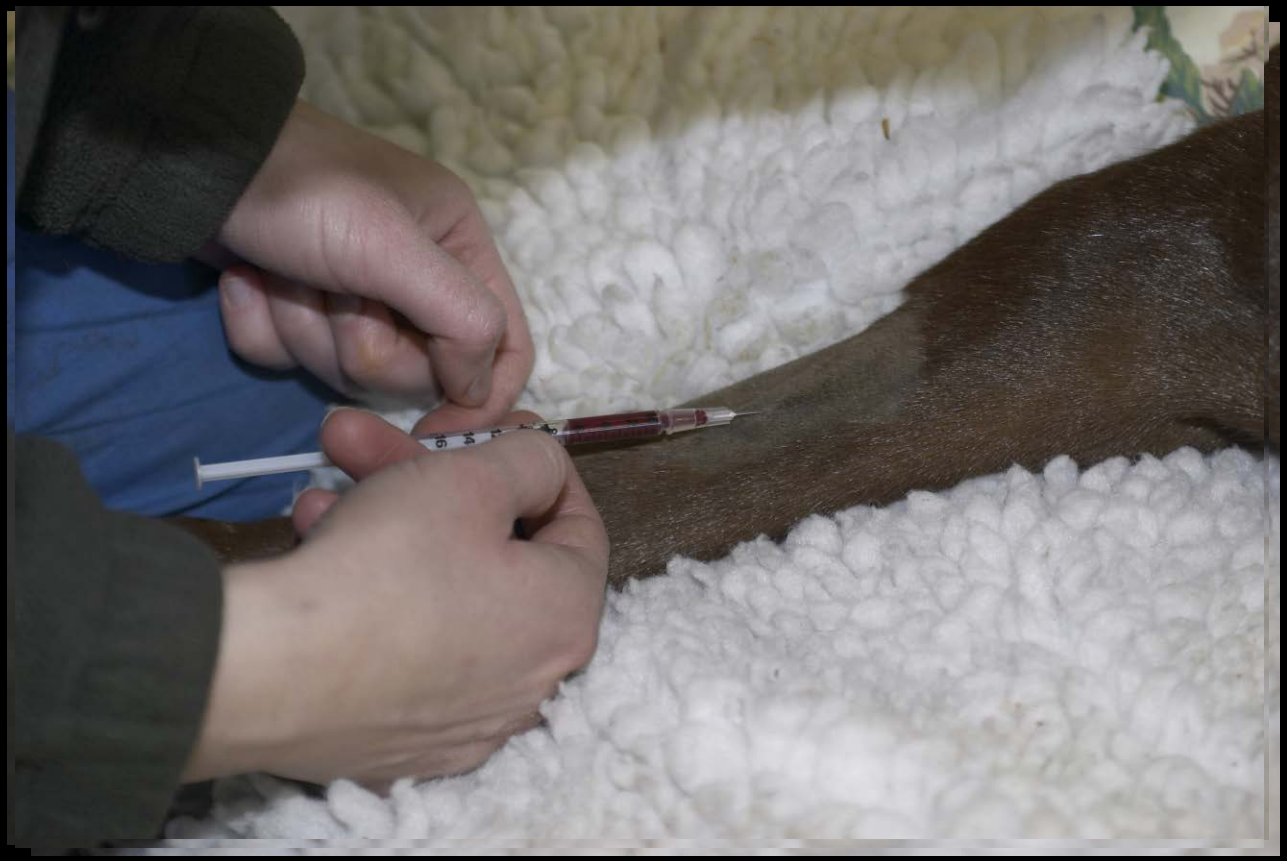
- Noninvasive predictor of $Paco_2$
  - Decrease arterial gas sampling
- Nasal sampling
  - Spontaneous breathing
  - Healthy lungs
  - No intranasal oxygen
  - Good estimate $PaCO_2$

Clinical Uses of Capnography

- Ventilation
  - Continuous capnography
  - If normal respiratory/cardiovascular physiology
    - Botulism foal
    - Continuous real time monitor adequate ventilation
      - $PETCO_2$ changes indicative of PaCO2 changes
      - Relationship of PETCO2/PaCO2 established
      - Assume changes in PETCO2 predict changes PaCO2

Clinical Uses of Capnography

- Alveolar hypoventilation
  - Increases $PaCO_2$ ∝ increase $PETCO_2$
- Confounding factors
  - (a-ET)PCO_2 difference
  - Simultaneous ABG/PETCO2 values noted
- (a-ET)PCO_2
  - Indicator of V/Q mismatching - pulmonary disease
  - (a-ET)PCO_2 difference widens
    - Predict the severity/progression respiratory disease

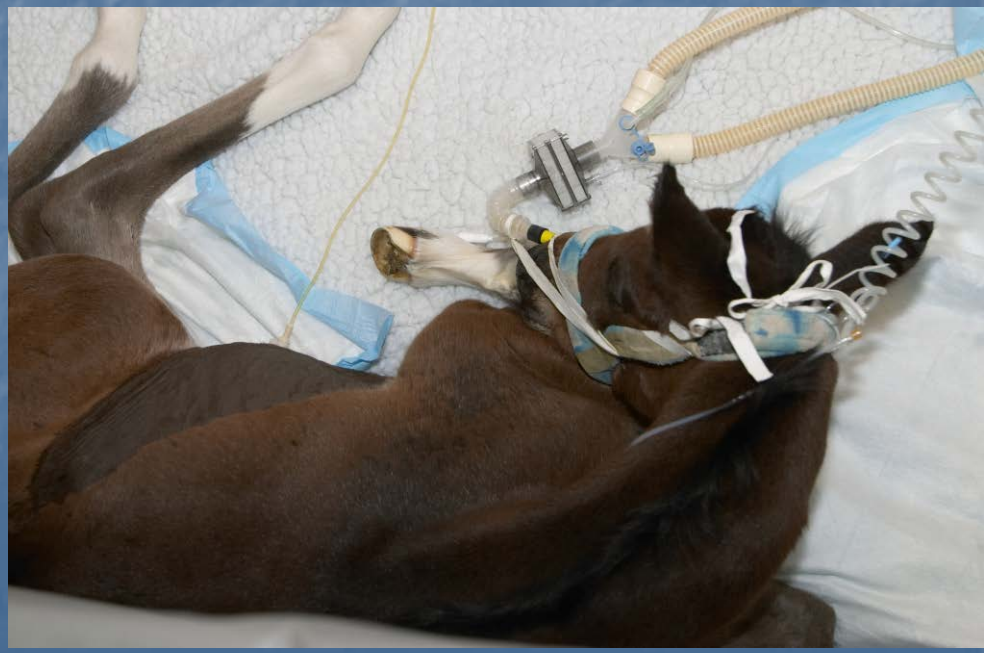


Clinical Uses of Capnography Ventilation

- 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

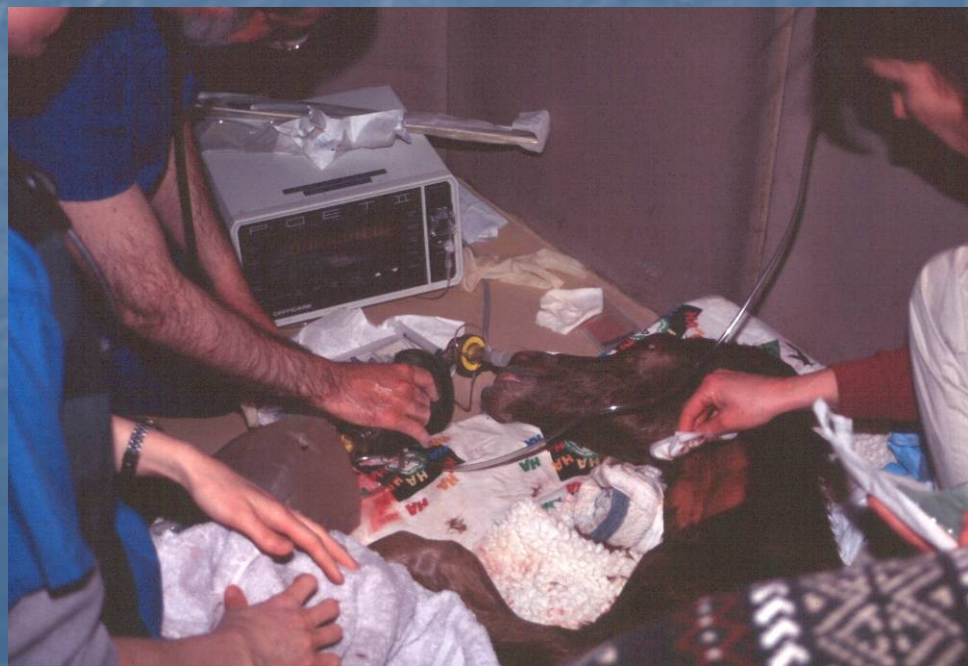
- ABG – pain/stress of sampling
- Capnography - evaluate $PaCO_2$ trend
- Monitor breathing pattern
- Monitor consistency of breathing
- Waveforms from spontaneous ventilation
  - Depth spontaneous breaths
  - Consistency of spontaneous ventilation

Clinical Uses of Capnography Cardiac Output

- Decreased cardiac output/pulmonary blood flow
  - Decrease in $PETCO_2$
  - Increase in (a-ET)$PC0_2$
  - % decrease $PETCO_2$ $\propto$ % decrease in CO
- Capnography ideal for monitoring cardiac output
  - CPR
  - EXIT
- As long as ventilation is constant
  - $PETCO_2$ is monitor of pulmonary blood flow

Clinical Uses of Capnography
CPR

- Cardiac arrest
  - No blood flow to lungs
  - $PETCO_2 = 0$
- Cardiac compressions
  - Low cardiac output
  - $PETCO_2$ 6-12
  - Very large ADV

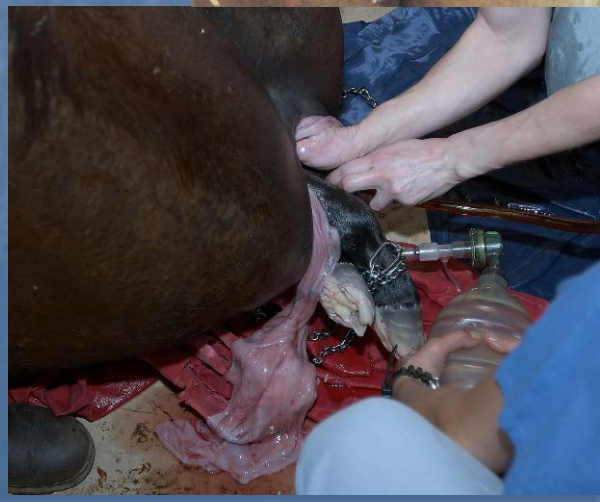


Clinical Uses of Capnography
CPR

- 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

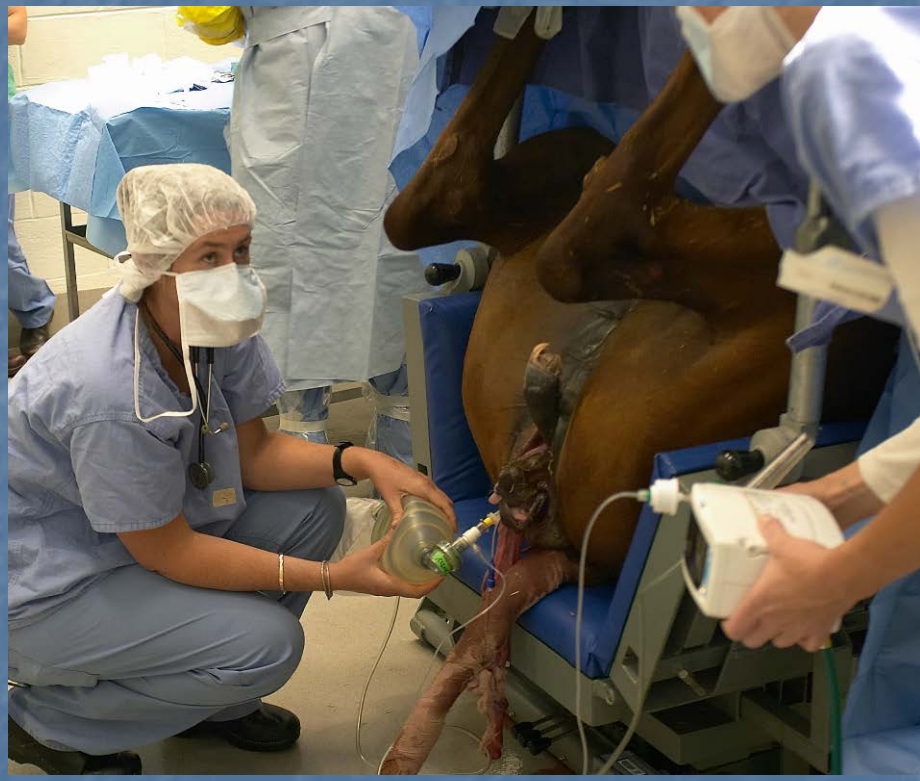
Clinical Uses of Capnography
EXIT

- EXutero Intrapartum Treatment
  - Beginning birth resuscitation during Stage II
  - Intubation and ventilation in the canal
- When ventilation is initiated
  - $PETCO_2$ very low – fetal circulation
- As lung is expanded by ventilation
  - Blood flow redirected to the lungs
  - CO to lungs increases
  - $PETCO_2$ increases



Clinical Uses of Capnography
EXIT

- $PETCO_2$ stays low or 0
  - CO compromised
- $PETCO_2$ > 40
  - Viable
  - Should continue to increase/stabilize
- $PETCO_2$ 10 – 20
  - Significant compromise
  - Rx IT epinephrine
- Caveats
  - Low $PETCO_2$ from hyperventilation
    - Operator error
  - Ventilation may cause cardiac pump
    - $PETCO_2$ 10-14
    - Nonviable foal

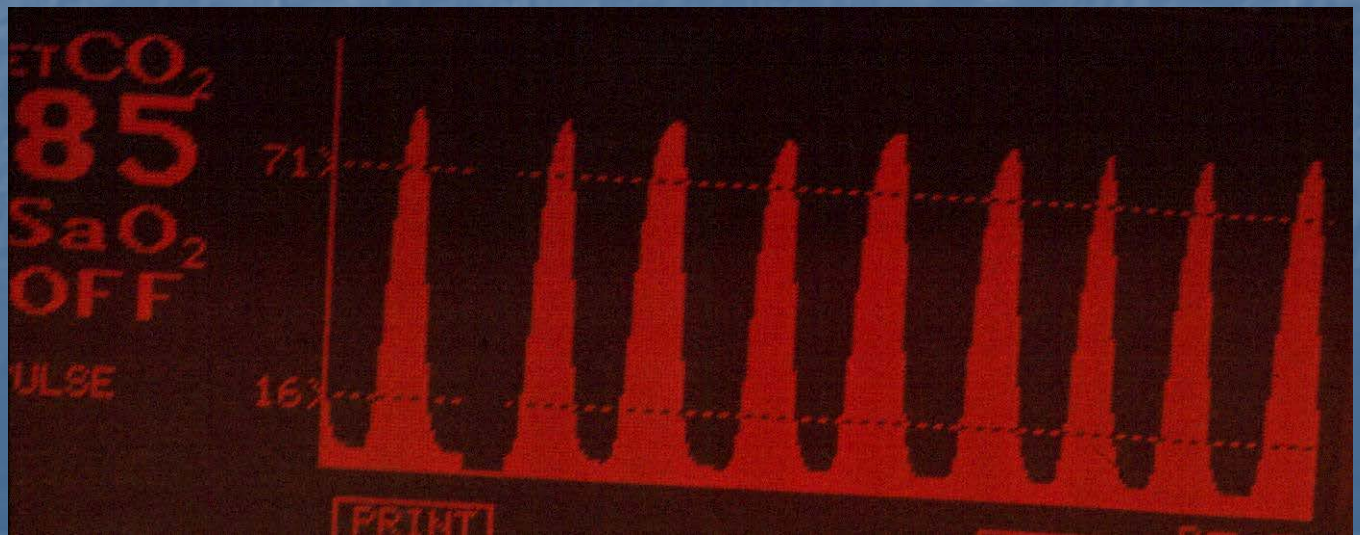


Clinical Uses of Capnography Progress of Pulmonary Disease

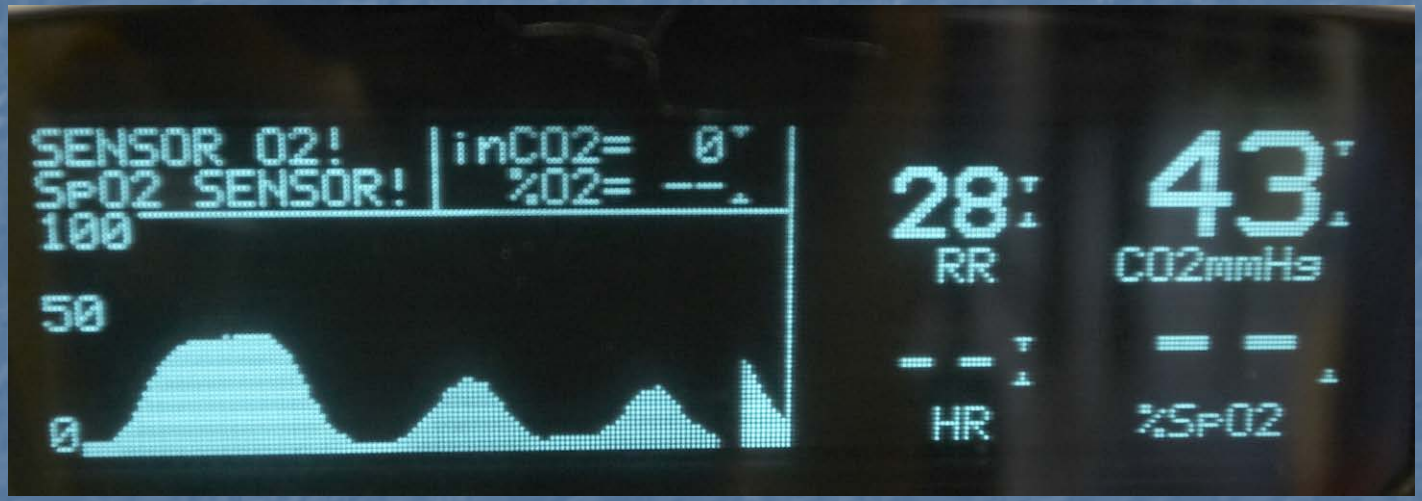
- Monitored by serial (a-ET)PCO_2
- Improved (a-ET)PCO_2 gradient
  - As the pulmonary disease improves
- Shape of capnogram
  - Increased V/Q mismatch
    - Increase slope of phase III
  - Airway disease
    - Various time constants
    - Prolonged phase II
    - Steeper phase III
  - Airway disease improves with therapy
    - Capnogram reverts to normal as V/Q ratios normalize

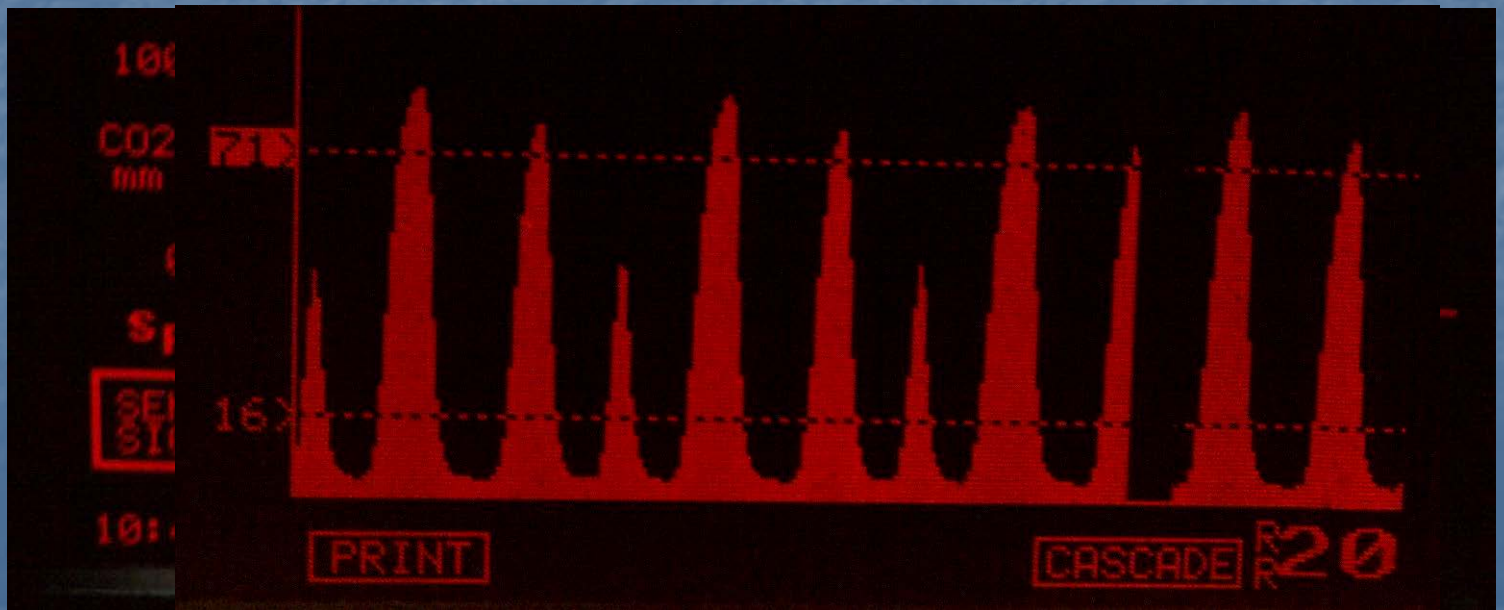
Clinical Examples

Capnography
No Plateau

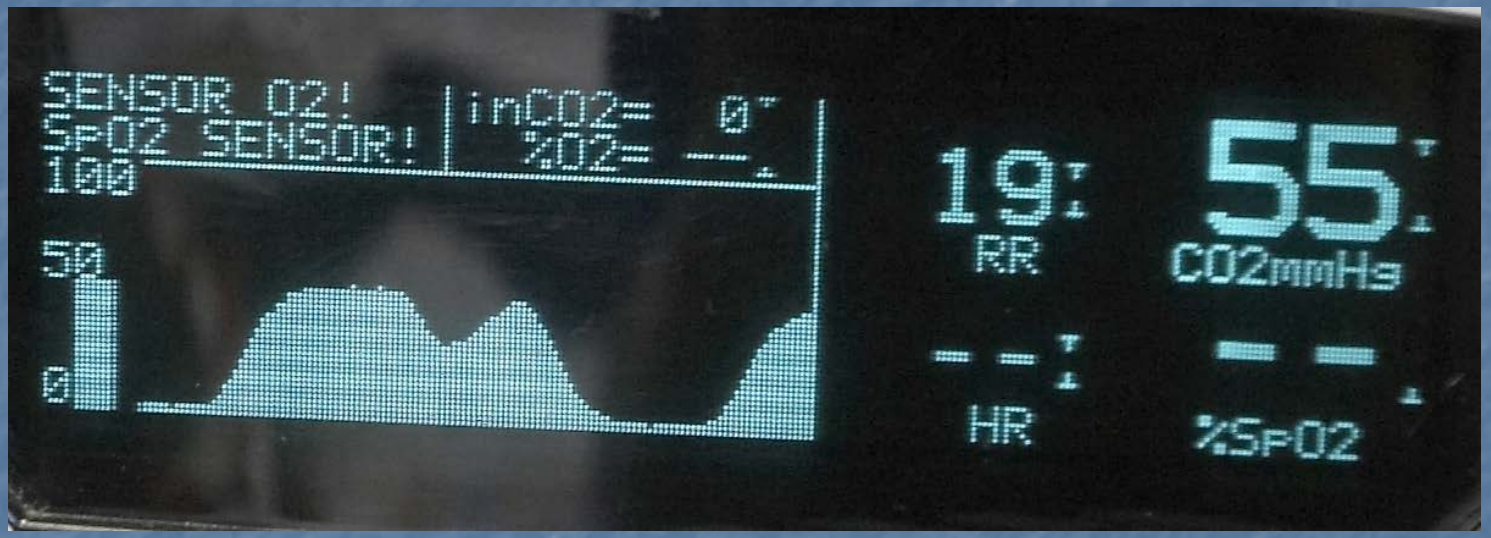


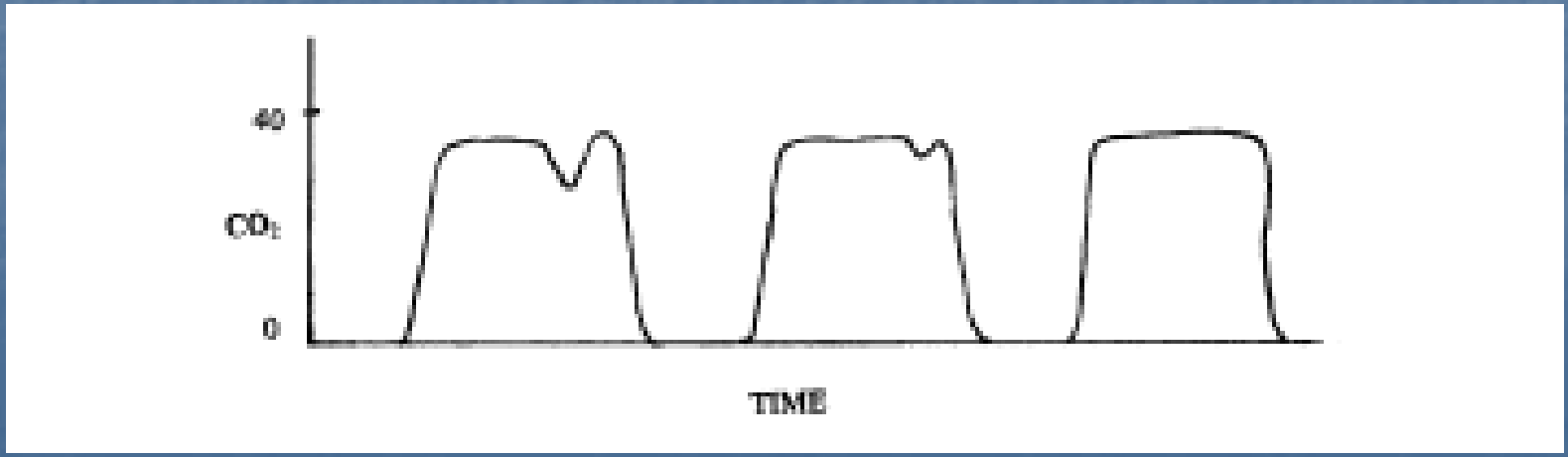
Capnography
Wave Variation



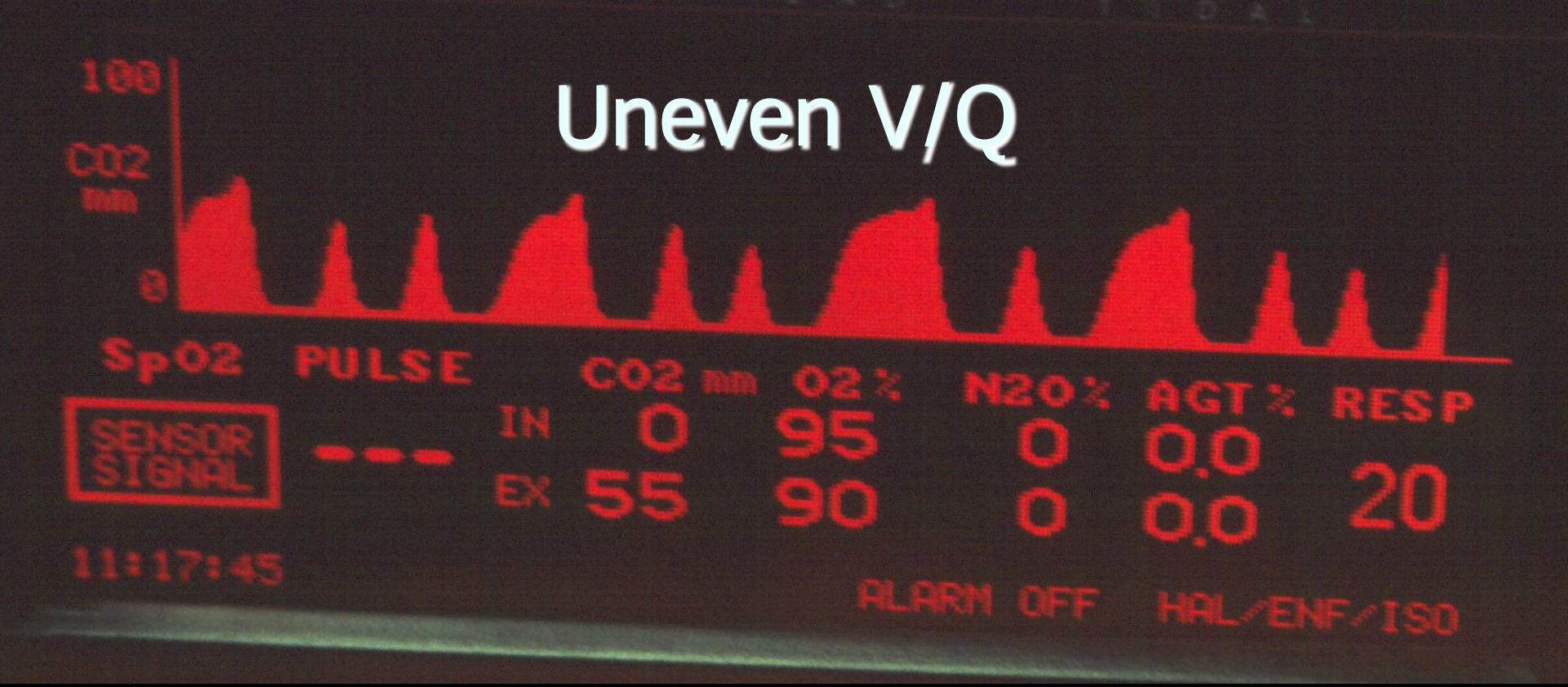


Capnography
Curare Notch

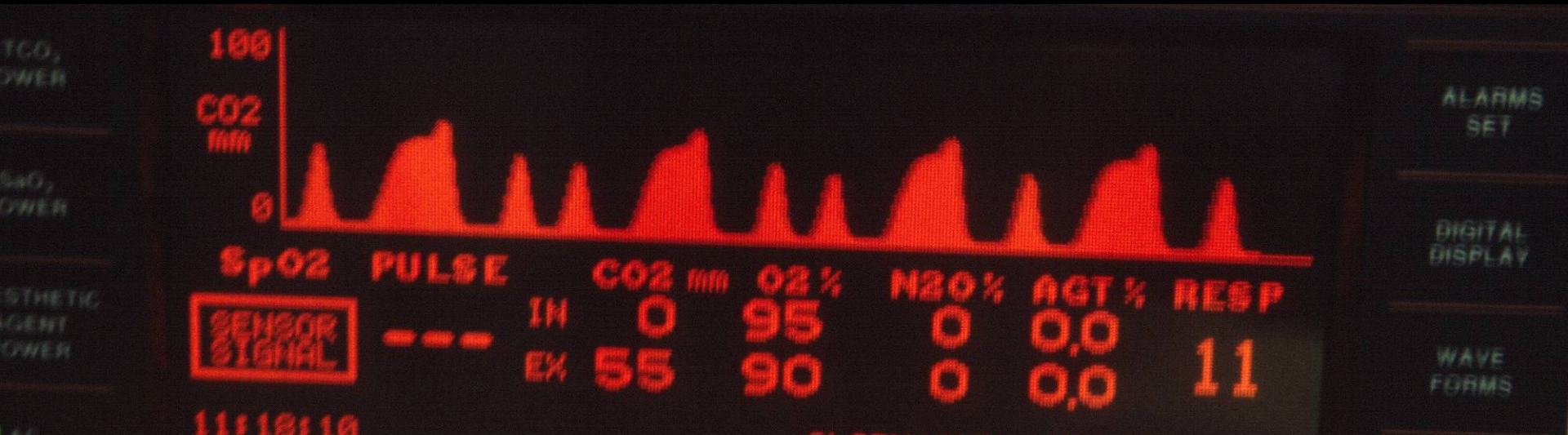




Uneven V/Q


100
CO2
mm
0
SpO2 PULSE
CO2 mm O2 % N2O % AGT % RESP
SENSOR SIGNAL

IN 0 95 0 0.0
EX 55 90 0 0.0 20
11:17:45
ALARM OFF HAL/ENF/ISO


100
CO2
mm
0
SpO2 PULSE
CO2 mm O2 % N2O % AGT % RESP
SENSOR SIGNAL

IN 0 95 0 0.0
EX 55 90 0 0.0 11
ALARMS SET
DIGITAL DISPLAY
WAVE FORMS

CAPNOGRAPHY:
A MONITORING TOOL WITH USUAL AND UNUSUAL APPLICATIONS

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The first infra-red CO_2 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 $PaCO_2$ capnography provides information about CO_2 production, pulmonary perfusion, alveolar ventilation, respiratory patterns, and elimination of CO_2 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 (CO_2 sensor located in the main unit and a tiny pump aspirates gas samples for measurement) is more practical than main-stream capnography (CO_2 sensor inserted between the breathing circuit and the endotracheal tube). Time capnography, which graphs the CO_2 concentration in the respiratory gas throughout the respiratory cycle, is commonly utilized. Volume capnography which graphs the accumulating CO_2 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 CO_2 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 $C0_2$. The color varies between expiration and inspiration, as $C0_2$ level changes. The color varies from purple (when exposed to room air or oxygen) to yellow (when exposed to 4% $C0_2$). The response time is fast enough to detect changes of $C0_2$ breath-by breath but is not very sensitive when CO_2 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 CO_2-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 CO_2-rich gas from the alveoli. Phase III almost always has a positive slope, indicating a rising PCO_2. There are several reasons for this upslope. First there is steady excretion of CO_2 into the alveoli even during expiration and as the alveoli volume decreases, the concentration of CO_2 during expiration increases. Second, late emptying of alveoli with long time constants have lower ventilation/perfusion ratios and, thus higher $C0_2$ concentrations. The inspiratory 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 $PETCO_2$ value measured. The results are encouraging in patients with healthy lungs, but controversial when the lungs are diseased.

The gradient between arterial and $PETCO_2$ is a useful index of alveolar dead space ventilation. Usually the $PETCO_2$ is lower than $PaCO_2$ 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 $PETCO_2$ gradient does not always reflect alveolar dead space. The (a-ET)PCO_2 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)$PC0_2$ 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 $PC0_2$) make more contribution to the $PETCO_2$, 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)$PC0_2$.

There are many other clinical uses of capnography. It is a simple, noninvasive predictor of $PaCO_2$, 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 $PaCO_2$. The (a-ET)PCO_2 gradient can vary depending on age and health of the lungs. Alveolar hypoventilation increases $PaCO_2$ as well as $PETCO_2$, making it an accurate reflection of changes in arterial values. But several factors can affect the (a-ET)PCO_2 difference and thus decrease the predictability of $PaCO_2$ from $PETCO_2$. Whenever an arterial blood gas is obtained, the simultaneous $PETCO_2$ should be noted so that (a-ET)PCO_2 can be assessed. The (a-ET)PCO_2 is an indicator of V/Q mismatching resulting from pulmonary disease. In neonates with respiratory disease, the (a-E_T)PCO_2 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, $PETCO_2$ values approximate $PaCO_2$ values and serve as a continuous real time monitor of adequacy of ventilation. In these cases, changes in $PETCO_2$ can often be regarded as indicative of changes in $PaCO_2$. A number of factors affect the relationship of $PETCO_2$ and $PaCO_2$. In these cases with normal pulmonary function once the relationship of $PETCO_2$ to $PaCO_2$ is established by blood gas analysis, changes in $PaCO_2$ may be assumed to occur in parallel with those in $PETCO_2$.

Capnography can identify problems with the ventilatory circuit instantaneously before O_2 and CO_2 levels change in the blood. In ventilated neonates with no spontaneous breathing, $PETCO_2$ falls to zero instantaneously following the disconnections in the circuit. However, in ventilated neonates breathing spontaneously, circuit disconnections distal to CO_2 sampling site (towards the neonate) can be identified as CO_2 concentration falls to zero, whereas, circuit disconnection proximal to the sampling site may not be detected as rapidly as $PETCO_2$ values depends on the adequacy of spontaneous breathing. If spontaneous breathing is adequate, the $PETCO_2$ values remain normal, whereas, $PETCO_2$ values may rise gradually if spontaneous breathing is inadequate. Capnography is also useful in giving an early warning of CO_2 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 CO_2 waveform (prolonged phase II and steeper phase III) and uneven height of the CO_2 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 PCO_2 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 $PaCO_2$, breathing pattern, and importantly the consistency of breathing before extubation. Evaluation of CO_2 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 $PETCO_2$ (end tidal Pco_2) and an increase in (a-ET)$PC0_2$ (the gradient between arterial and end tidal Pco_2). The percent decrease in $PETCO_2$ 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 $PETCO_2$. Consequently alveolar dead space is reduced as is (a-ET)$PC0_2$. As long as lung ventilation is constant (a very important criteria), $PETCO_2$ 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 $PETCO_2$ and an increased (a-ET)PCO_2 gradient. During CPR or EXIT, as pulmonary blood flow increases, the $PETCO_2$ increases as alveolar dead space decreases and the (a-ET)PCO_2 gradient becomes smaller. $PETCO_2$ is a function of cardiac output for any given ventilation making $PETCO_2$ a noninvasive monitor of pulmonary blood flow. $PETCO_2$ monitoring can be used to monitor the effectiveness of cardiopulmonary resuscitation. During cardiac arrest, circulation ceases and as long as ventilation continues, $PETCO_2$ gradually disappears, reappearing only when circulation is restored either by effective cardiac compressions or return of spontaneous cardiac output. $PETCO_2$ can be used to determine the most effective technique of cardiac compression for the individual and insure that cardiac output is present. $PETCO_2$ monitoring may have a prognostic and if it remains minimal for greater than 10 minutes, cardiopulmonary resuscitation is futile.

Monitoring $PETCO_2$ 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 $PETCO_2$ will be very low as the fetal lung receives little cardiac output. As the lung is expanded by ventilation, blood in redirected away from the placenta and to the lungs. As pulmonary cardiac output increases, so will the $PETCO_2$. If it doesn't, it means that cardiac output is compromised. During the EXIT procedure, $PETCO_2$ monitoring is vital in directing therapy and predicting vitality.

Progress of pulmonary disease can be monitored by improved serial (a-ET)PCO_2. As the pulmonary disease improves the initial abnormal (a-ET)PCO_2 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.