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Original Article

Carbon Dioxide monitoring (capnography)

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Unlike the arterial blood gas analysis which is the gold standard for measuring CO2 levels in the arterial blood, capnography measures exhaled breath CO2 concentration non-invasively over time giving the capnogram or the CO2 waveform. Variations in end-tidal CO2 (EtCO2) may be used to assess the severity of an illness and the effectiveness of a therapy, while changes in the structure of the capnogram itself can be used to diagnose specific disorders. CO2 monitors use either the mainstream or sidestream settings to assess gas concentration or partial pressure. Capnography has many clinical applications in the emergency department, operating theaters, intensive care units, both in the intubated and spontaneously breathing patients.

Definition

Capnography refers to the non-invasive measurement of CO_2 levels in exhaled breath, typically plotted as CO_2 concentration over time. The CO_2 waveform, also known as a capnogram, visually represents the connection between CO2 concentration and time. While variations in end-tidal CO2 (EtCO2), the maximum CO2 concentration at the conclusion of each tidal breath, may be used to assess the severity of an illness and the effectiveness of a therapy, changes in the structure of the capnogram can be used to diagnose specific disorders. Capnography is the most conclusive proof that an endotracheal tube is properly positioned within the trachea after a successful intubation.[1]

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Principles of operation

- CO_2 monitors use either the mainstream or sidestream settings to assess gas concentration or partial pressure.[2]
- Most standard devices measure CO_2 directly from the airway, with the sensor positioned on the airway adapter at the center of the endotracheal tube (ETT).[3]
- By taking a little sample of exhaled breath via a nasal or nasal-oral cannula and sending it via tubing to a sensor inside the monitor, these sidestream devices determine the CO_2 levels.
- Most standard systems are typically set up to accommodate patients who have been intubated.
- Dual-purpose sidestream systems are set up for patients who are intubated as well as those who are not.

Figure (1): $EtCO_2$ mainstream [1]

Figure (2): End tidal CO_2 ($EtCO_2$) monitor sidestream [1]

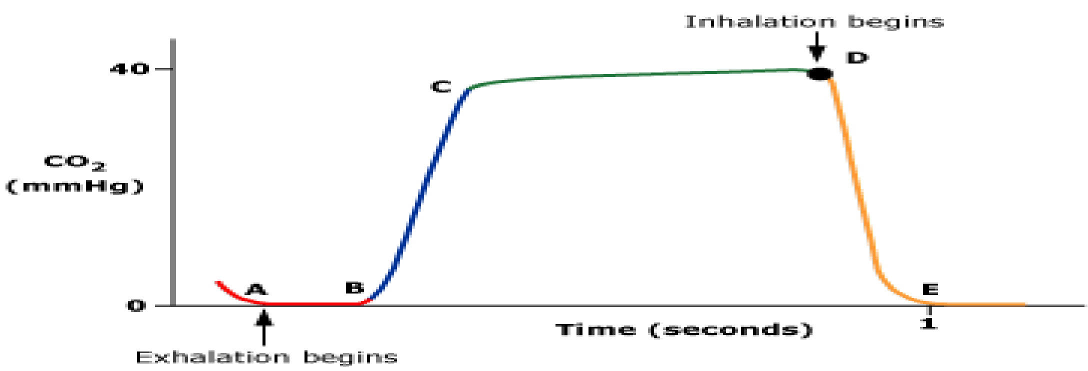
- There are two types of CO_2 monitors: quantitative and qualitative[3]:
- Quantitative devices can take a numerical reading (capnometry) or a numerical reading along with a waveform (capnography) to determine the exact $EtCO_2$.
- Colorimetric detectors and other qualitative devices do not provide an exact number for

$EtCO_2$, but rather a range (e.g., 0 to 10 mmHg or >35 mmHg).

- The colorimetric $EtCO_2$ detector utilizes litmus paper that undergoes a color change upon exposure to CO_2. The paper turns purple for $EtCO_2$ levels below 3 mmHg, tans for levels between 3 and 15 mmHg, and yellow for levels beyond 15 mmHg.
- The main purpose of this tool is to confirm the placement of ETTs. The litmus paper will become yellow when CO_2 is exhaled from an ETT inserted into the trachea.

➢ **Normal CO_2 Waveform** here are four stages to the capnogram[5]:

- Phase 1: (dead space ventilation, a-b) denotes the start of exhalation, when the upper airway's dead space is removed and the CO_2 concentration becomes closer to zero.
- Phase 2: As CO_2 from the alveoli enters the upper airway, the concentration of CO_2 in the respiratory stream rapidly rises (ascending phase, b-c).
- Phase 3: (alveolar plateau, c-d) occurs when the CO_2 content in the whole respiratory stream, from the alveoli to the nose, reaches a constant level. Point D, located at the base of the alveolar plateau, is properly called $EtCO_2$ because it reflects the highest concentration of CO_2 at the end of a tidal breath. This is the numerical value seen on the screen.
- Phase 4: (d-e) is the inspiratory cycle, during which the CO_2 level returns to zero.



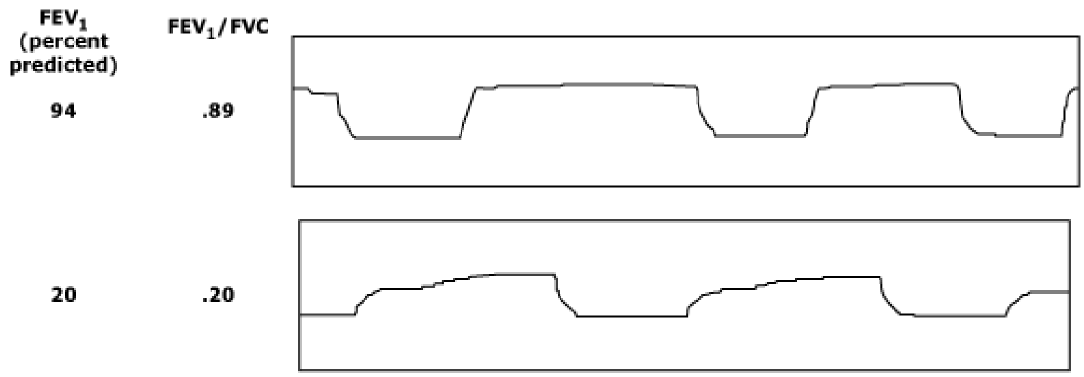
A - B: Dead Space Ventilation
B - C: Ascending Expiratory Phase
C - D: Alveolar Plateau
D: End-tidal CO_2
D - E: Descending Inspiratory Phase

Figure (3): Normal CO_2 Waveform[7]

- **A normal capnogram (i.e., a valid breath)**
- A CO_2 level that starts at zero and goes back to zero, a maximum CO_2 concentration that is reached with each breath (as determined by $EtCO_2$), an amplitude that is directly correlated with $EtCO_2$ concentration, a width that is influenced by expiratory time, and a characteristic shape typical of normal lung function are some of the key characteristics that define this condition, which affects patients of all ages [5] The amplitude is determined by the level of EtCO2, the width is influenced by the duration of expiration, CO_2 levels begin at zero and revert back to zero, a peak CO_2 concentration is achieved with each breath as measured by EtCO2, and normal lung function displays a distinct shape across all age groups[5]
- The distinctive trapezoidal capnogram and little change between the arterial CO_2 concentration ($PaCO_2$) and alveolar CO_2 concentration ($EtCO_2$), which range from 0 to 5 mmHg, are characteristics of people with normal lung

function. The typical gradient of is caused by the gas in the physiologic dead space. [5]

- The difference between $EtCO_2$ and $PaCO_2$ increases in proportion to the severity of lung dysfunction and ventilation-perfusion mismatch in patients.
- Only assessing changes in ventilatory status over time is possible with the $EtCO_2$ in individuals with lung illness; isolated $EtCO_2$ readings may or may not correlate with the $PaCO_2$ [6]



With its characteristic rectangular shape, this waveform is indicative of a patient with a normal lung function.
A patient with severe chronic obstructive pulmonary disease is seen in the bottom waveform, which has an upward slope of the alveolar plateau and a characteristic curved shape.

Figure (4): CO_2 waveform in obstructive lung disease. [7]

- **Clinical applications**

I. Capnography can also be employed in patients who have had a tube inserted into their airway for:

- Confirmation of the correct positioning of an endotracheal tube (ETT).
- Continuous tube placement monitoring throughout transportation.
- Predicting outcomes during cardiac arrest and assessing the effectiveness of resuscitation.
- Return Of Spontaneous Circulation (ROSC) indicator when performing chest compressions.
- The EtCO2 levels in individuals who may have high intracranial pressure should be adjusted.
- Assessing the outcome in traumatic injuries.
- Assessing the sufficiency of ventilation.

❖ **Return of spontaneous circulation**

- During cardiac arrest, $EtCO_2$ is the first sign of the restoration of spontaneous circulation (ROSC). [9]
- Chest compressions can be safely stopped to assess blood pressure and heart rhythm following this rise in $EtCO_2$ [10,11]

❖ **Factors that can complicate resuscitation attempts.**

- Drugs used in resuscitation may affect $EtCO_2$ values 11.
- $EtCO_2$ levels typically drop quickly following the administration of epinephrine. [10]
- Following return of spontaneous circulation (ROSC), sodium bicarbonate may lead to a temporary increase in exhaled carbon dioxide ($EtCO_2$), however the increase in $EtCO_2$ levels is more pronounced and sustained compared to a sodium bicarbonate bolus. [10]

❖ **Cardiac arrest prognosis**

- $EtCO_2$ levels of ≤10 mmHg measured 20 minutes after the initiation of Advanced Cardiovascular Life Support (ACLS) accurately predicted death in adult patients with cardiac arrest. [12]

❖ **Increased Intracranial Pressure (ICP) and trauma prognosis**

- The level of CO_2 in the arteries impacts the flow of blood to the brain. Elevated CO_2 levels cause cerebral blood vessels to dilate, whereas decreased CO_2 levels lead to cerebral vasoconstriction.
- Hypoventilation lasting over time (characterized by $PaCO_2$ levels of 50 mmHg or above) leads to increased blood flow to the brain and increased intracranial pressure, posing a risk to individuals who have suffered a head injury. Sustained hyperventilation, characterized by a $PaCO_2$ level of ≤30 mmHg, is also disadvantageous and linked to poorer neurological outcomes in patients with severe brain injuries. Therefore, the Brain Trauma Foundation recommends breathing rates to achieve eucapnia. Research has shown that hemorrhagic shock and mortality are linked to low ECO_2 in trauma patients. [13]

II. Special applications in RICU. [25]:

A. Diagnosis of PE in MV patients:

1) Through the detection of alveolar dead space:
- $PACO_2$ is mid-point of phase 3 of capnography
- $PECO_2$ is $EtCO_2$
- Anatomical dead space is phase 1 of capnography

Alveolar dead space = physiological dead space – anatomical dead space Alveolar dead space = pulmonary embolism

2) Calculation of alveolar dead space fraction:
- Normally the difference between $PACO_2$ and $PaCO_2$ is 5 mmHg which represents the anatomical dead space.
- Causes of hypoventilation/hyperventilation increase/decrease both $PACO_2$ and $PaCO_2$ so the difference remains constant.
- In cases of increased dead space as in PE, the difference between $PACO_2$ and $PaCO_2$ increases.

Alveolar dead space fraction = ($PaCO_2$ – $EtCO_2$)/$PaCO_2$

If >0.15 …. PE

If <0.15 … PE less likely

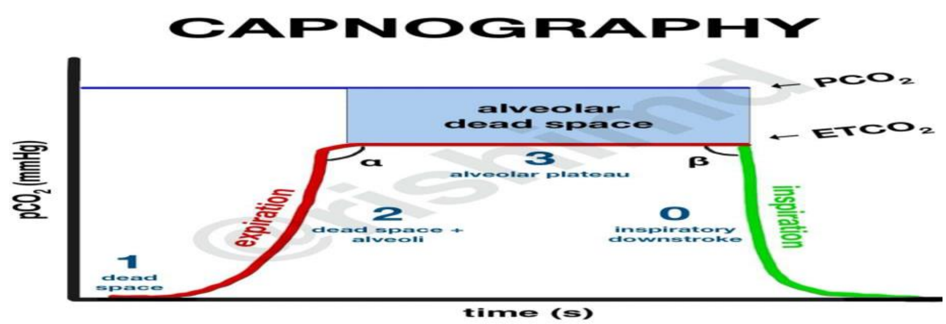


Figure (5): Calculation of alveolar dead space fraction using capnography

B. Follow up after reperfusion therapy for PE:

- After thrombolytic therapy administration for PE, follow up of alveolar dead space fraction can differentiate between patients with effective thrombolysis and those who might need catheter directed therapy or surgery.
- Serial reduction in the alveolar dead space fraction denotes effective thrombolysis with improving V/Q matching.
- Also, decreasing the slope of phase III in capnography denotes decreasing alveolar dead
- space fraction and improving V/Q matching. [25]

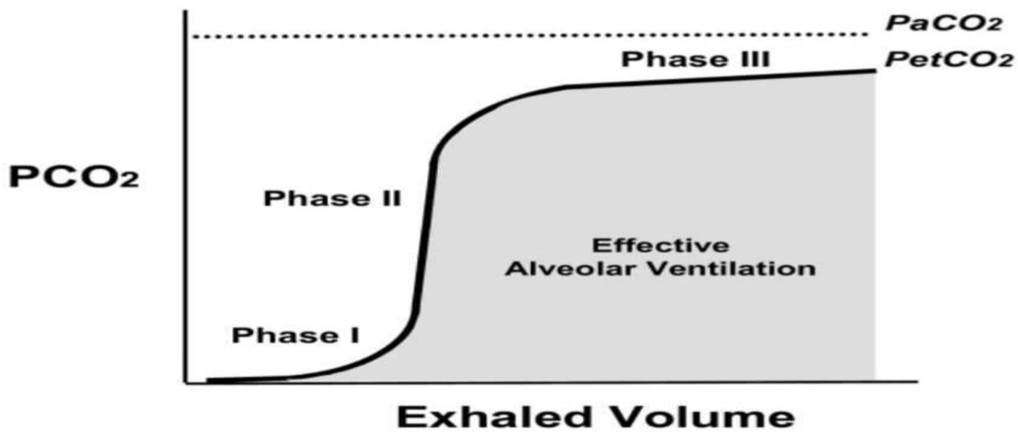


Figure (6): Effective alveolar ventilation

C. Capnography in pneumothorax:

- In MV patients, presence of high $EtCO_2$ effectively exclude tension pneumothorax as tension pneumothorax leads to circulatory collapse with decrease VR and hence CO_2 flow from alveoli [25].
- In pressure-controlled ventilation, pneumothorax causes decrease in tidal volume as pressure is already controlled and so hypoventilation due to decrease in TV and increase CO_2 in blood then **increase end tidal CO_2** provided that it`s not tension pneumothorax.[27]
- In Volume controlled ventilation, pneumothorax causes increase in airway pressure which may decrease COP causing **decrease in $EtCO_2$** like in tension pneumothorax.[27]
- High airway pressure and high $EtCO_2$ … pneumothorax must be excluded.[27]
- High airway pressure and low $EtCO_2$ … tension pneumothorax … proceed for urgent needle decompression.[27]
- Patient on MV diagnosed with pneumothorax and has high $EtCO_2$ and then begin to decrease … tension pneumothorax.[27]
- One of earliest sign of tension pneumothorax is decrease end tidal CO_2 and may even just before circulatory collapse.[27]

D. Best PEEP on ventilator using capnography "Volume Capnography"

- In ARDS, if after increasing the external PEEP the Carbon Dioxide production (VCO_2)increases this mean that PEEP led to recruitment of collapsed alveoli >>> improvement of oxygenation >>> improvement of pulmonary vasoconstriction >>> increase left ventricle preload >>> increase in COP >>> improvement in tissues perfusion with oxygenated blood >>> improvement in aerobic metabolism >>> increase CO_2 production. [26]
- If after increasing the external PEEP the VCO_2 decreases this means application of excessive PEEP leading to decrease COP and hence CO_2 production and PEEP must be decreased.[26]

E. Calculation of Cardiac Output (COP) "Capnodynamic"

In patients with cardiogenic shock e.g., due to MI, improving COP means effective therapeutic intervention e.g., after thrombolytic therapy.[28]

$$Q = VCO_2 / (CvCO_2 - CaCO_2)$$

- **Carbon Dioxide production (VCO_2)**: from capnography
- **Carbon Dioxide content in central venous blood ($CvCO_2$):** from central line blood sample
- **Carbon Dioxide content in arterial blood $CaCO_2$:** from ABG sample

III. Capnography can be used in spontaneously breathing, non-intubated patient for:

1. Quickly evaluating individuals who are seizing or in serious condition.
2. Assessing how well a patient is responding to therapy for acute respiratory distress.
3. Assessing the effectiveness of breathing in patients who are unconscious or obtunded, or in patients receiving procedural sedation.
4. Identifying metabolic acidosis in children with gastroenteritis and diabetes patients.
5. Offering prognostic markers to individuals suffering from septic shock or sepsis.

1. **Assessing airway, breathing, and circulation:**

- Using the capnography waveform and end-tidal carbon dioxide (EtCO2) values, patients' airway, breathing, and circulation (ABCs) may be rapidly assessed. A normal waveform indicates the presence of a patent airway and spontaneous breathing. Adequate ventilation and perfusion are indicated by normal EtCO2 levels ranging from 35 to 45 mmHg. Capnography can be employed to evaluate patients who are unresponsive, encompassing those experiencing active seizures as well as those affected by chemical terrorism. Capnography offers accurate readings even in low perfusion situations, unlike pulse oximetry, which can be misled by motion artifact and provide unreliable results. [14] Capnography offers accurate values in low perfusion situations and does not misunderstand motion artefact, in contrast to pulse oximetry. [14]

2. **Seizures:**

- Since capnography depends only on respiratory activity and is unaffected by muscular activity or movement artefacts, it is the only monitoring technique that can give accurate and trustworthy data on patients with active disorders. [15]
- Respiratory rate, $EtCO_2$, and capnogram are examples of capnographic data that may be used to distinguish between distinct states. [16] Capnographic information (capnogram, respiratory rate, and $EtCO^2$) can be used to differentiate between. [16]

- Patients who show signs of apnoea, such as a flatline waveform, no detectable movement of the chest wall, and an absence $EtCO_2$ measurement, are taken into custody.
- Recognizing patients with low end-tidal carbon dioxide ($EtCO_2$) levels and tiny waveforms, which indicate insufficient ventilation.
- Patients who are being effectively ventilated, with a normal CO_2 waveform and normal $EtCO_2$ values.

3. **Acute respiratory distress:**

- Capnography offers real-time tracking of a patient's respiratory condition in cases of severe breathing difficulties stemming from various sources such as asthma, heart failure, and chronic obstructive pulmonary disease (COPD). Capnography gives immediate input on the patient's clinical state by monitoring respiratory rate and $EtCO_2$ with each breath. [17]
- People with obstructive lung disease experience poor breathing out and inconsistent alveoli emptying caused by a mismatch between air delivery and oxygen supply, and their lung function tests show an increased steepness in the initial part of the breathing out curve and an upward trend in the plateau [6]. Apart from having a more rounded increase in breath and an upward sloping alveolar plateau [6], individuals with obstructive lung disease also experience decreased expiratory airflow and uneven

- emptying of the alveoli due to ventilation-perfusion mismatch.

a) Using an oral or nasal cannula to measure the respiratory rate directly from the airway (mouth and nose) yields a more accurate measurement than impedance respiratory monitoring.

Even if the patient is not breathing, impedance monitoring in upper airway blockage and laryngospasm detects movement in the chest wall, interprets this as a legitimate breath, and shows a respiratory rate. Capnography, on the other hand, displays a flatline waveform and detects no ventilation.

b) $EtCO_2$ trends may be quickly evaluated by clinicians. This gives enough information to assess if the patient's breathing is improving (decreasing $EtCO_2$), stabilising (steady $EtCO_2$), or getting worse despite therapy (increasing $EtCO_2$). When respiratory muscle exhaustion or a more severe lower airway blockage develops in an acutely tachypneic patient with obstructive lung disease, for instance, rising $EtCO_2$ would indicate deteriorating ventilation.

4. Procedural sedation:

- Common adverse airway and respiratory events linked to procedural sedation and analgesia (PSA), such as respiratory depression, apnea, upper airway obstruction, laryngospasm, and bronchospasm, can be quickly identified with capnography.[18]
- Compared to patients monitored in a traditional manner, patients monitored using capnography had a much lower frequency of hypoxic episodes. This is particularly true given the provision of supplementary oxygen reduces the effectiveness of pulse oximetry as an early warning system for respiratory depression during PSA.[19]

Before pulse oximetry notices a declining oxyhemoglobin saturation, oversedation-induced respiratory depression, particularly in patients on supplemental oxygen, will exhibit unusually high or low $EtCO_2$. 60 seconds was the median interval between the start of hypoxia and respiratory depression as determined by $EtCO_2$.[20]

✓ **Flatline waveform:**

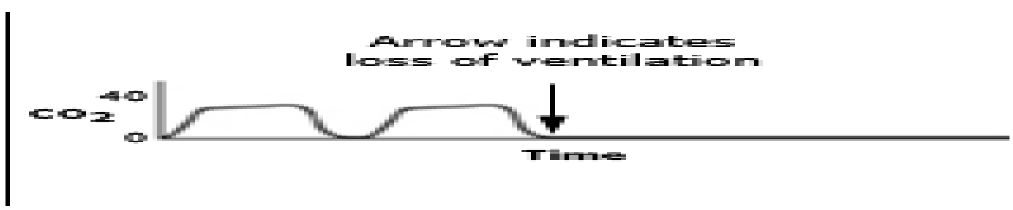


Figure (7): Flatline waveform [8]

This situation can arise due to:

1-The monitor calibration will display a "calibrating" message on the screen. calibration of the monitor (will show "calibrating" on the monitor).

2-The monitor will show "occlusion" due to cannula occlusion, or the monitor will show "occlusion" due to cannula occlusion.

3-Respiratory conditions include obstructive or central apnoea. central or obstructive apnoea.

.

In contrast to obstructive apnoea, which usually manifests with chest wall movement because of upper airway blockage or laryngospasm, central apnoea is characterised by the absence of chest wall movement and a flatline waveform.

Response to airway alignment manoeuvres, such as the jaw push and chin raise, can help distinguish between laryngospasm and upper airway blockage

Increasing waveform height:

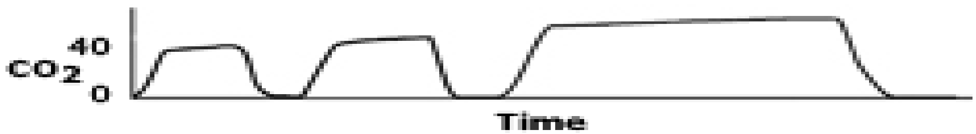


Figure (8): Increasing waveform height [8]

This occurs with **bradypneic hypoventilation** and reflects increasing $EtCO_2$.

- ✓ ***Decreasing waveform height:***

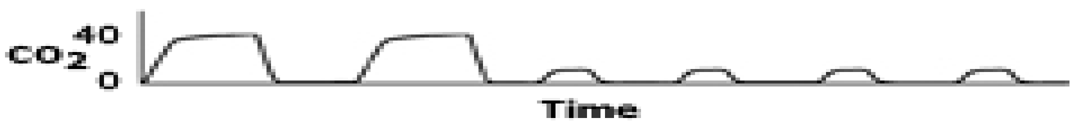


Figure (9): Decreasing waveform height [8]

This occurs with hypopneic hypoventilation (i.e., low tidal volume breathing) and reflects decreasing

- ✓ ***Increasing waveform width:***

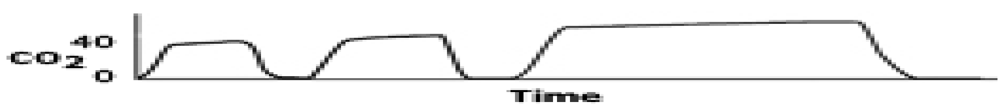


Figure (10): Increasing waveform width [8]

This occurs with hypoventilation and increasing expiratory time.

- ✓ ***Decreasing waveform width:***

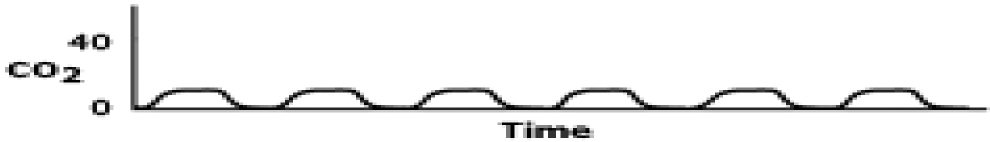


Figure (11): Decreasing waveform width [8]

This occurs with hyperventilation and decreasing expiratory time.

- ***Curved/shark-fin appearing waveform:***

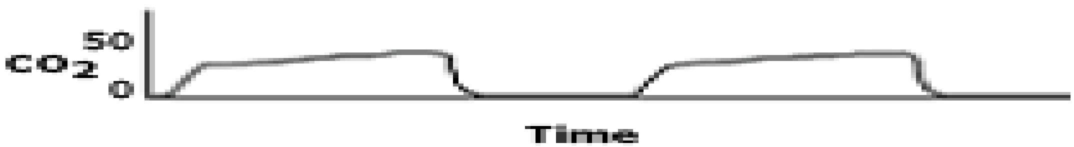


Figure (12): Shark-fin waveform [8]

A patient with obstructive lung illness (such as asthma, COPD, or cystic fibrosis) may exhibit the distinctive curving capnogram, which also signals bronchospasm in those without chronic lung disease.

- ***Small waveforms interspersed with flatline waveforms:***

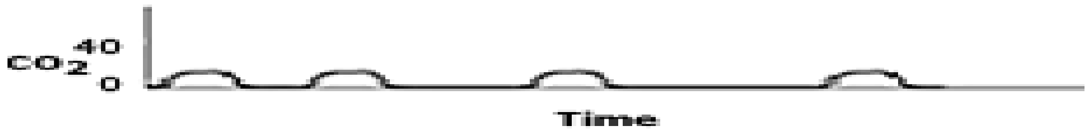


Figure (13): Irregular waveform [8]

This irregular waveform pattern occurs with hypopneic hypoventilation and indicates periodic breathing.

5. **Detecting metabolic acidosis:**

- In children with gastroenteritis and individuals with diabetic ketoacidosis, capnography can be utilised as a marker of metabolic acidosis. Lower HCO^{3-}, greater respiratory rate, and lower $EtCO_2$ are all associated with more acidotic patients.[21]
- Additionally, $EtCO_2$ can be used to differentiate diabetics with ketoacidosis (metabolic acidosis, compensatory tachypnea, and low $EtCO_2$) from those without (nonacidotic, normal respiratory rate, and normal $EtCO_2$).[22]

6. **Prognosis in sepsis:**

$EtCO_2$ levels and lactate levels have a reversible relationship in sepsis, severe sepsis, and septic shock.[23] In sepsis, severe sepsis, and septic shock, lactate levels and $EtCO_2$ have an inverse connection.[23] In individuals with suspected sepsis, $etCO_2$ predicts death similarly to lactate.[24]

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