Noninvasive Monitoring of Gas Exchange During Testing

Robertson Chapter 12

Overview

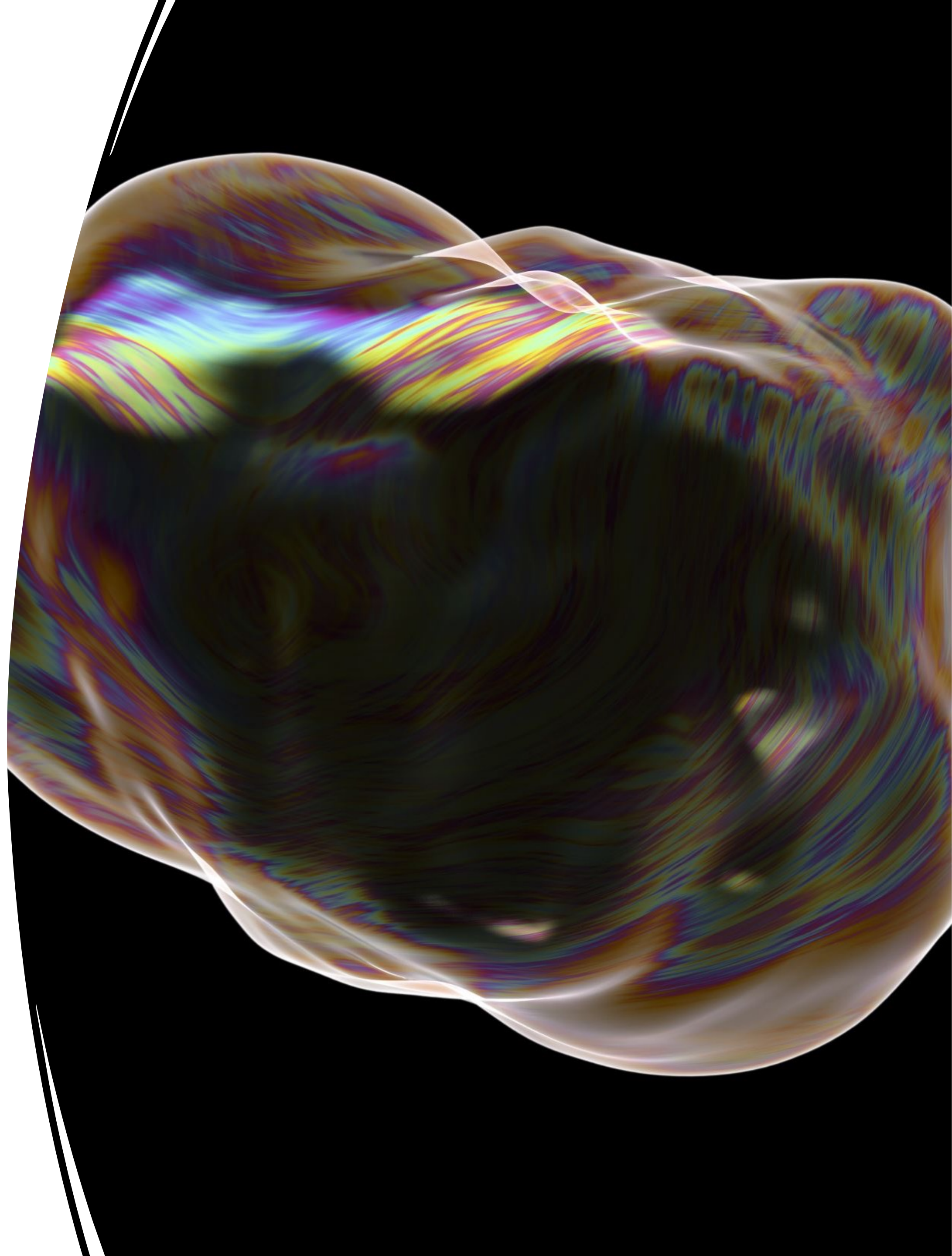
- Involves obtaining O2 or CO2 values without skin puncture or invading the body
- Most common:
  - Pulse oximetry → O2Hb saturation
  - ETCO2 or tcCo2 for CO2
- Each device has limitations and advantages

Overview of Gas Exchange

- Oxygenation values = Amount of O2 carried by circulating blood
- Internal respiration = Process of gas diffusion between arterial blood and tissue at cellular level
- Diffusion = Movement of molecules, driven by a pressure gradient, across a semipermeable membrane

Overview of Gas Exchange

- External respiration = Gases diffuse within the lungs across the alveolar-capillary membrane, where pulmonary capillaries and alveoli interface
- Inhaled air = 20.95% O_2
- Respiration occurs only at cellular level
- Ventilation = Gross movement of air into and out of lungs
  - Moves gases between external environment and alveoli



Hypoxia

Hypoxia = Inadequate tissue oxygenation

Hypoxemia = Low amounts of O2 in blood

Hypoxic hypoxia = Tissue oxygenation diminished because of low amounts of O2 in inspired air

Majority of O2 transported by blood is carried to tissues in from of oxyhemoglobin (O2Hb)

Affinity of CO for Hb is about 210 times the affinity of O2 for Hb

Anemic hypoxia = Hb impairment responsible for blood's reduced O2 carrying capacity

Hypoxia

- Circulatory hypoxia = Blood flow stagnant and doesn't deliver adequate O2 to body
- Histotoxic hypoxia = Tissues become toxic and cells unable to use O2 being delivered
  - Oxygenation appears better than actual results
- Lung disease can cause hypoxia
  - COPD
  - Obesity hypoventilation
  - Restrictive lung disorders

Monitoring Oxygenation and Ventilation

- Oxygenation most commonly measured by ABG or pulse oximetry
  - Less commonly by transcutaneous
  - PaO_2 = ABG measurement
  - $tcPO_2$ = Transcutaneous measurement
  - SpO_2 = Pulse oximetry measurement
- Pulse oximeter = Non-invasive monitor for estimating saturation of Hb with O_2
  - ABG value is calculated value not estimated like pulse oximetry
    - ABG = Gold standard of monitoring O_2 and CO_2

Oxygenation Status Classification

PaO2	SpO2	Oxygenation Status
80-100 mm Hg	95%-100%	Normal
60-80 mm Hg	90%-95%	Mild hypoxemia
40-60 mm Hg	70%-90%	Moderate hypoxemia
< 40 mm Hg	< 70%	Severe hypoxemia

Monitoring CO_2

- $PaCO_2$ = ABG measurement
- During hypoventilation, CO_2 in blood rises
  - Above 45 mm Hg = Hypercapnia (hypercarbia)
- During hyperventilation, CO_2 in blood decreases below 35 mm Hg
- 2 noninvasive measurements:
  - $ETCO_2$ = Sampling exhaled gas at end exhalation
  - $tcPCO_2$ = Transcutaneous

Arterial Values of Blood Gases

- PaO_2 = Gold standard for determining oxygenation status
- Cooximetry = Additional test run in conjunction with ABG analysis that provides direct measurement of O_2Hb saturation, abnormal Hb, and total Hb

Blood gas parameter	Arterial Value
pH	7.35-7.45
$PaCO_2$	35-45 mm Hg
HCO_3^-	22-26 mEq/L
PaO_2	80-100 mm Hg

Assessment of pH Values

- Normal pH = 7.35-7.45
  - Even slight change can be life threatening
    - If < 6.8 or > 7.8, cellular metabolism starts to stop, and death ensues
    - Metabolic component of acid-base balance assess based on HCO_3^- value
      - Normally 22-26 mEq/L
      - HCO_3^- changes show changes in renal system
    - Respiratory component is $PaCO_2$
      - Hypoventilation = > 45 mm Hg
      - Hyperventilation = < 35 mm Hg

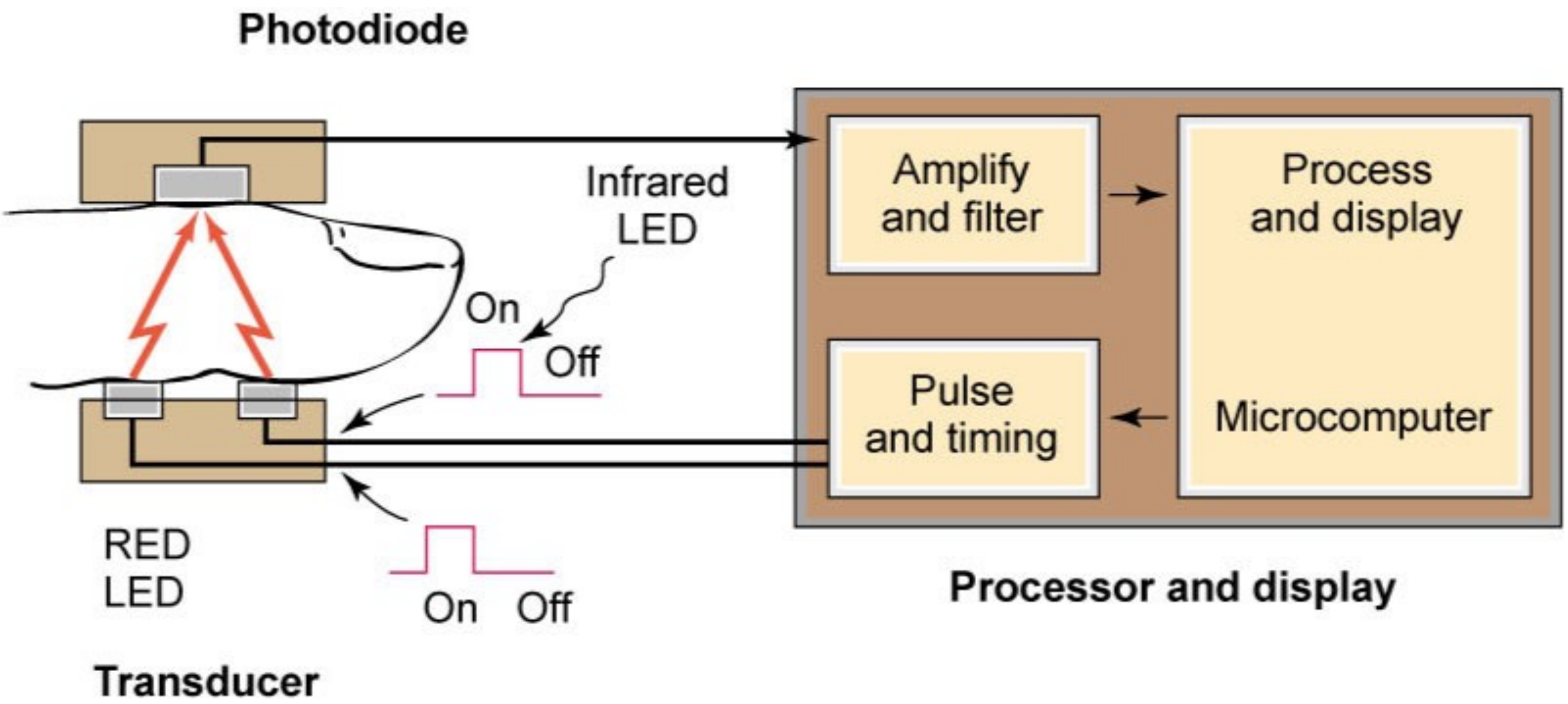
Assessment of pH Values

- PaCo2 = “Acid”
  - When increased, pH more acidic and decreases
  - When decreased, pH more alkaline and increases
- HCO3- = “Base” (alkaline component)
  - When increased, causes upward shift in pH
  - When decreased, causes downward shift in pH
- Balance between acid and base responsible for pH value
  - Must be maintained for normal physiologic function

Pulse Oximetry

- Often referred to as “fifth vital sign”
- Simple, noninvasive technique to monitor tissue oxygenation
- Data obtained through probe placed on each side of vascular bed (finger, ear, or toe)
  - Data represents % of saturated Hb with O2
- SpO2 = Saturation of peripheral O2
  - Measured by pulse oximetry
- SaO2 = Saturation of arterial O2
  - Measured by ABG

Pulse Oximetry



Modified from Gardner RM: J Cardiovasc Nurs 1:79, 1987.

Origins of Pulse Oximetry

- Dates back to early 1930s but no great interest until WWII
- Early 1940s – Glen Millikan developed lightweight ear O2 meter for aviation monitoring
  - Coined term oximeter
  - Modified throughout 1940s and 1950s
  - Eventually manufactured by Waters Company
- 1970s – HP marketed system for use in clinical setting
  - Was bulky, heavy (35 lbs), and expensive ($10,000)

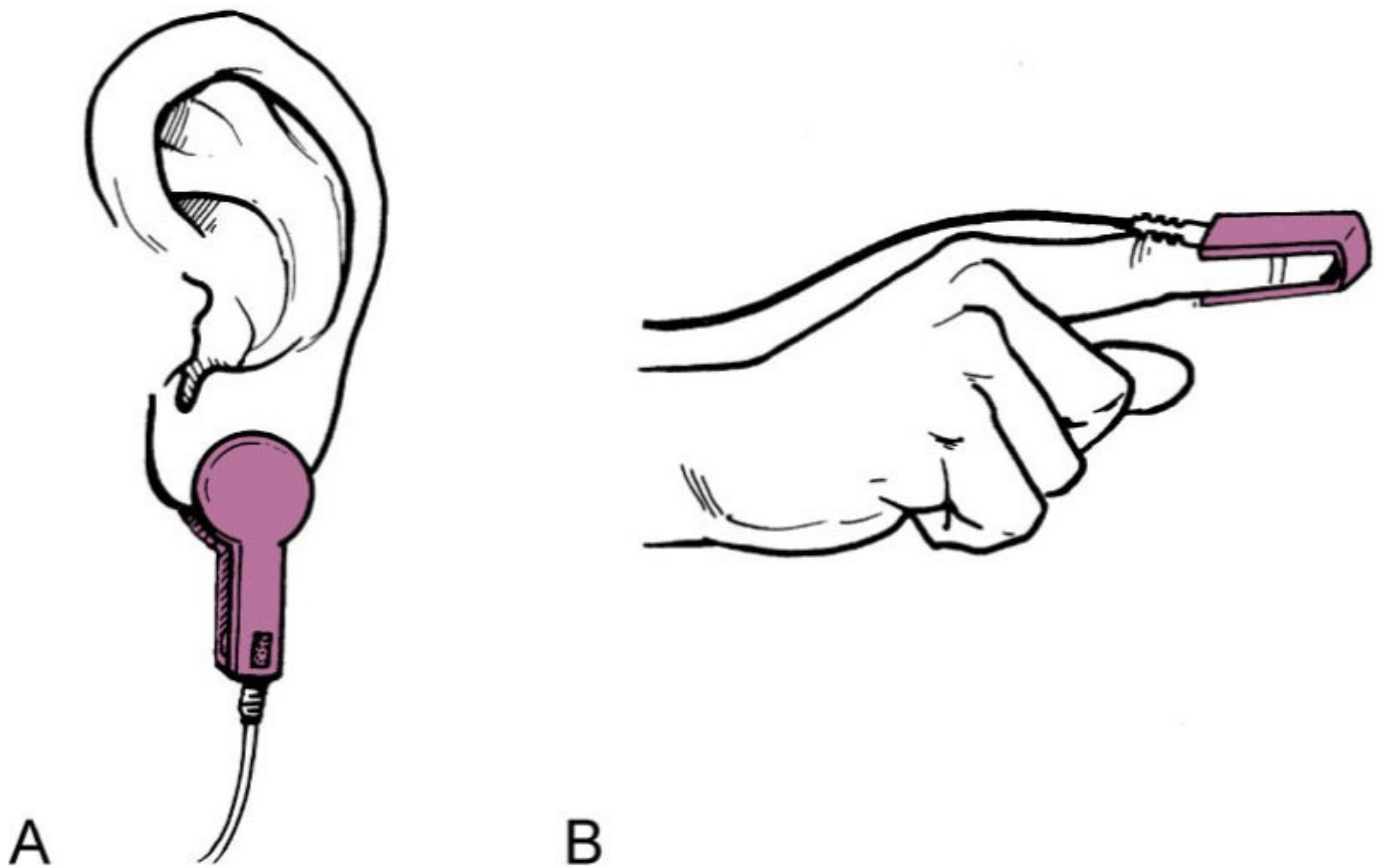
Origins of Pulse Oximetry

- 1972 – Modern oximeter developed by Takuo Aoyagi
- 1980 – Nellcor introduced first reliable and affordable oximeter commercially available
- Reusable sensors must be thoroughly cleaned and disinfected between patients
- There is a slight delay between acutal oxygenation changes and the change in displayed value on pulse oximeter

Reusable Adult Clip-Type Pulse Oximeter

From Elkin MK, et al: Nursing interventions and clinical skills, ed 4, St Louis, 2008, Elsevier.

Pulse Oximeter Sensors



From Linton AD: Introduction to medical-surgical nursing, ed 5, St Louis, 2012, Elsevier.

Theory of Pulse Oximetry Operation

- Use principles of spectrophotometry and photoplethysmography to estimate % of saturated Hb in blood
  - Spectrophotometry – Every substance has own pattern of light absorption
    - Pattern varies predictably with amount of substance that is present
    - Represents venous and capillary blood flow
  - Photoplethysmography – Uses light to detect minute volume changes between baseline and pulsatile component of blood flow through tissue bed
    - Represents arterial blood flow through tissue

Theory of Pulse Oximetry Operation

- Uses 2 wavelengths of light: Red and infrared
- Transmitted light consists of 2 components:
  - DC component = Large, fixed component
    - Represents light passing through tissue and venous blood without being absorbed
  - AC component = Smaller portion pulsatile in nature
    - Changes absorption as blood pulses through arterioles
- Pulse oximeter divides AC signal by DC signal at each wavelength

Oximetry Contraindications and Precautions

- Contraindications:
  - Presence of ongoing need for measurement of pH, $PaCO_2$, Hbtot, and abnormal hemoglobins
  - Allergy to sensor material
- Precautions:
  - Burns due to prolonged use
  - Too tight→ Pressure injury
  - Inspect device, power cord, and input cable for damage prior to use
  - Should be regularly tested for excessive electrical leakage current
  - Power cord should never be altered
  - Do not use incompatible probes

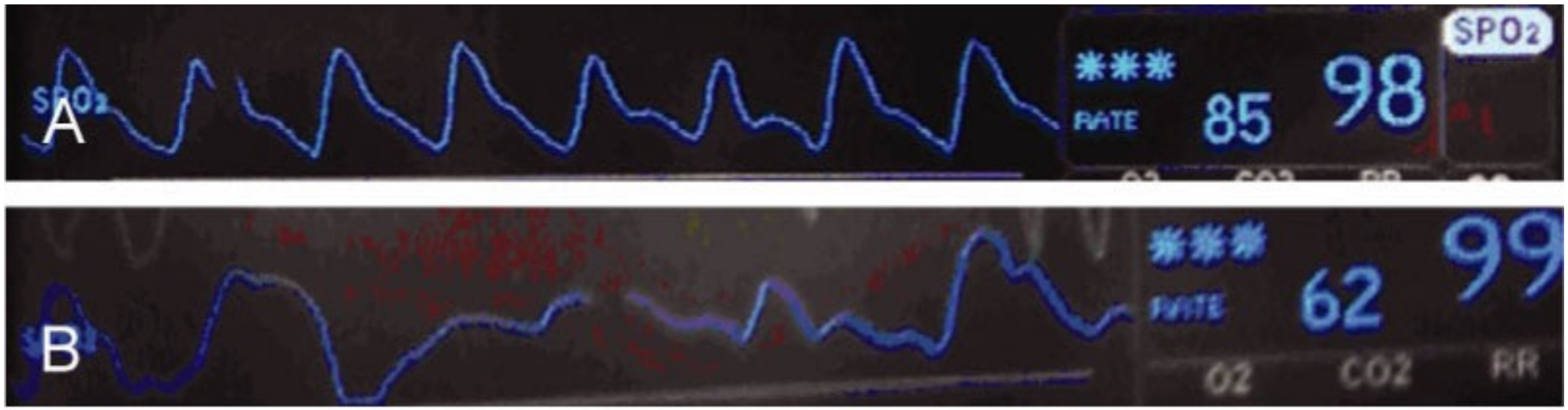
Oximetry Infection Control

- Wear gloves
- Thoroughly clean and disinfect after each patient use for reusable probes
  - Also clean extension cable and oximeter itself after each use
- Throw away disposable probes after each use

Limitations to Testing and Reliability of Results

- Techs should always attempt to correct problems and document what was tried
- Oxyhemoglobin Dissociation Curve
  - Oximeters estimate % of Hb that is saturated but cannot determine what Hb is saturated with
    - Can show a high O2 reading even when patient has abnormally elevated levels of CO in Hb
    - May also present with clinical hypoxia even though showing normal % on oximeter
  - Peripheral perfusion, hypoxemia, hypotension, cold extremities, peripheral vasoconstriction, or reduction in diameter of blood vessels can make getting valid oximetry data difficult

Plethysmographic Waveforms for Oximetry



From Sandberg WS, et al: The MGH textbook of anesthetic equipment, ed 1, Philadelphia, 2011, Elsevier-Saunders.

A. Normal plethysmographic waveform
B. Abnormal, unreliable plethysmographic waveform

Additional Considerations for Pulse Oximetry Monitoring

- Nail coverings and nail polish should be removed prior to use
- Consider clinical issues that could potentiate increased motion artifact
- Make sure to properly place the sensor
  - Transducer and photodiode should lie directly across a vascular bed from one another
- Memory capacity, sampling rate, averaging time (response time), and data output capabilities can affect readings

Factors Resulting in Erroneous Oximetry Values

Factor	Effect on SpO2 %
Nail polish	Falsely high
Dark skin pigmentation	Falsely high
Presence of COHb	Falsely high
High metHb	Falsely low if > 85% Falsely high if < 85%
Presence of fetal Hb	None
Anemia	None or low
Ambient light	Varies
Movement	Unpredictable
Poor perfusion	Poor signal; varies
Hypothermia	Poor signal; varies
Hypotension	Poor signal; varies

Optimizing Oximetry During PSG

- AASM requires a max signal averaging time of 3 seconds for pulse oximetry during PSG
- Most oximeters interfaced with PSG acquisition systems provide 0-1 volt DC signal
- Tech must be proficient at troubleshooting equipment problems

Recording Oximetry Data

- Operation manuals should be read for oximeters interfaced with PSG system
- Oximetry calibration
  - Simple procedure
  - Most oximeters generate calibration signals of 0 V and 1 V, representing 0% and 100% SpO_2
- Selecting appropriate oximeter
  - Use the fastest response time setting available
  - CMS policy on supplemental O_2 is ≤ 88% for ≥ 5 minutes during sleep
  - Oximetry alone not sufficient for diagnosis
  - CMS and AASM require an associated O_2Hb desat to score a hypopnea

Monitoring Ventilation During Sleep

- Blood CO_2 levels provide most accurate representation of adequacy of ventilation
- To score hypoventilation in adults:
  - Increase in $PaCO_2 \geq 10$ mm Hg during sleep to value exceeding 50 mm Hg for ≥ 10 minutes, or an increase to value > 55 mm Hg for ≥ 10 minutes
  - Measured by ABG, $ETCO_2$, or $tcCO_2$
    - $ETCO_2$ and $tcCO_2$ primarily used in pediatrics

Impact of Hypoventilation During Sleep

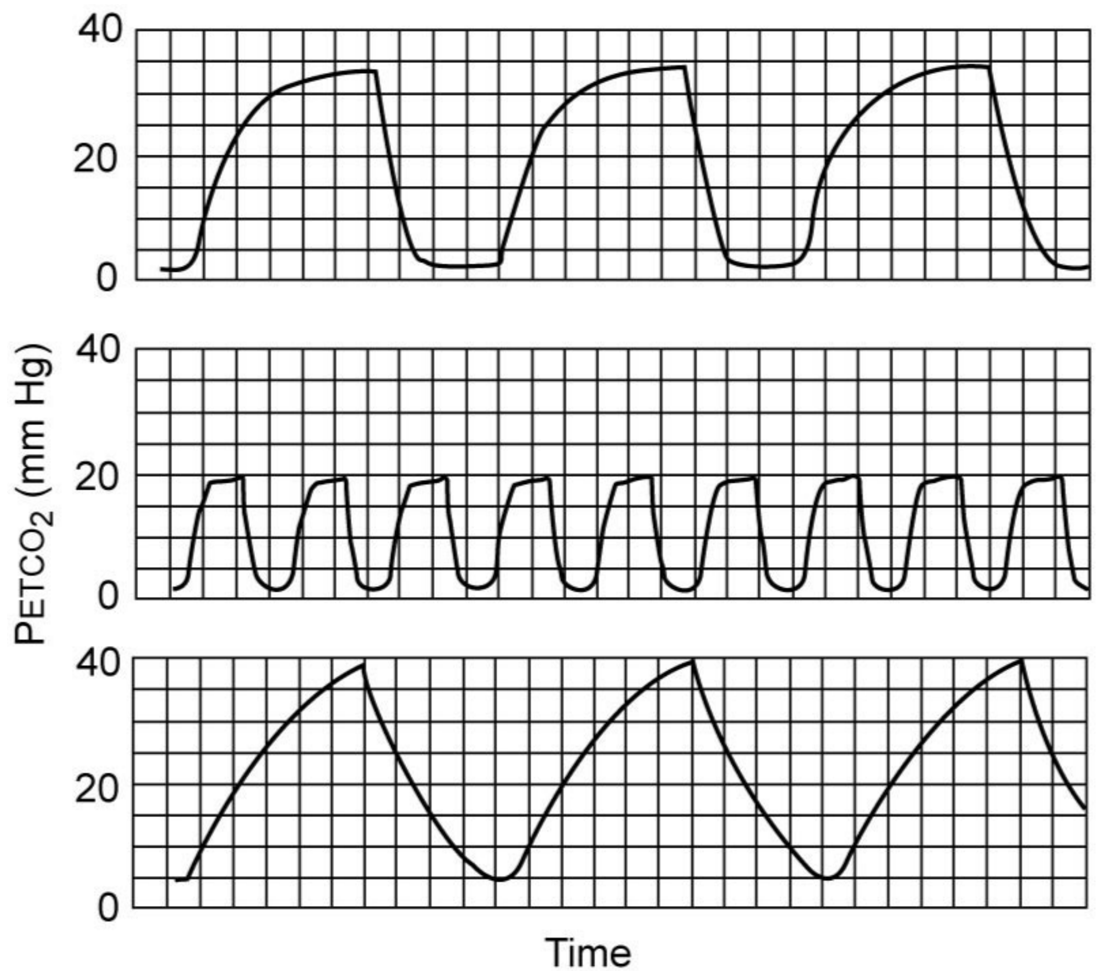
- Everyone has elevated CO_2 levels during sleep compared with wake values
- Normal adults experience increase in $PaCO_2$ of 2-8 mm Hg during NREM and 5-10 mm Hg during REM
- Underlying medical disease or SDB may cause patients to hypoventilate enough to affect pH
  - This compromises metabolic function
- Most labs don’t monitor CO_2
  - This can affect titration outcomes

ETCO2 Monitoring

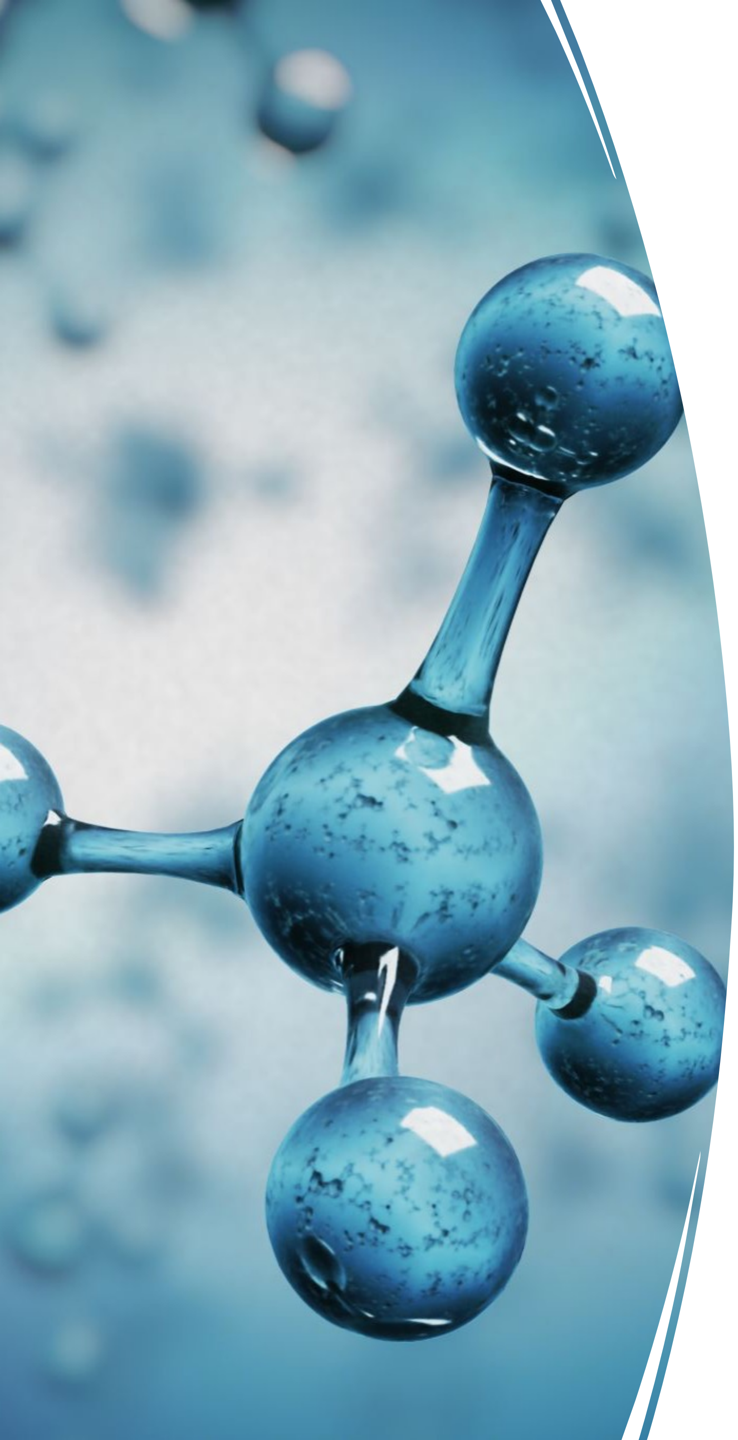
- Also known as capnometry or capnography
- Can provide info on patient’s breathing pattern, underlying respiratory disease, and SDB events
- Often see increase in ETCO2 before desat in SpO2
- Often only used in pediatrics

Monitoring CO2 in Adults

- **Top:** Normal Pattern
- **Middle:** Hyperventilation
- **Bottom:** Ventilation-perfusion mismatching



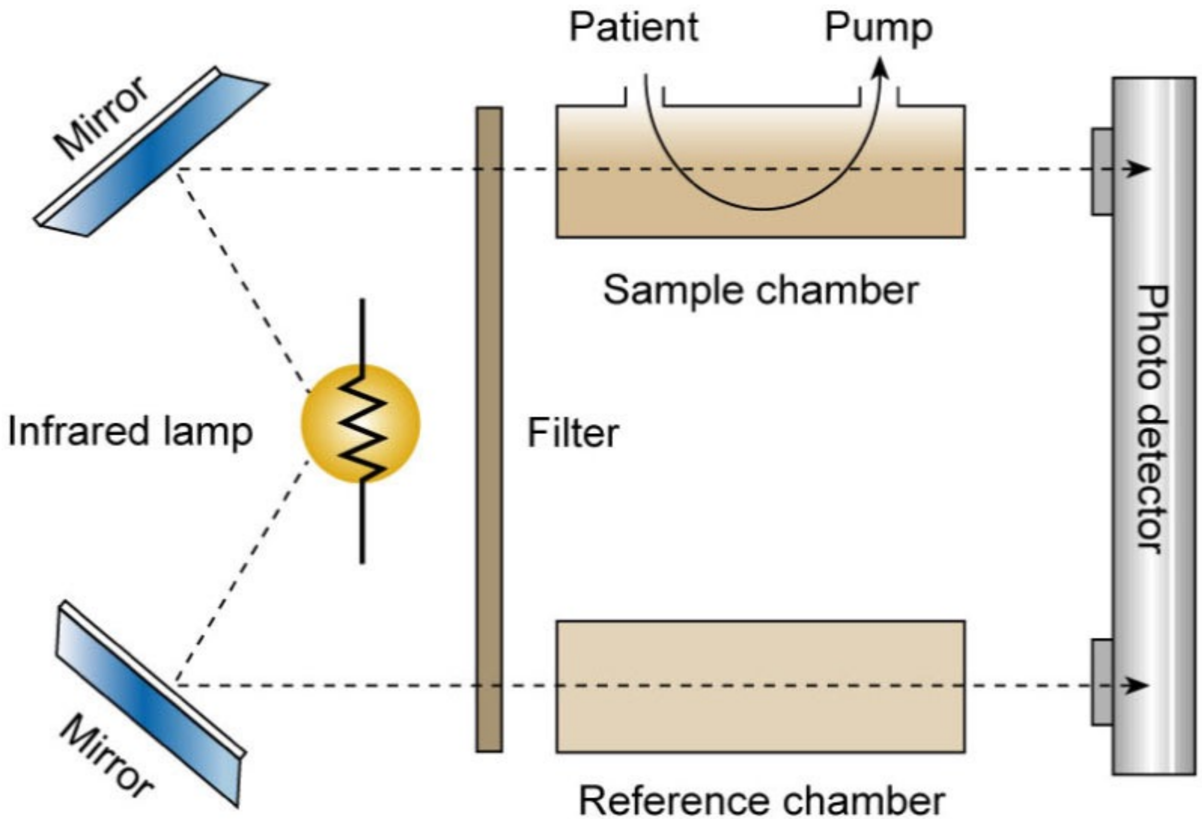
From Ruppel GL: Manual of pulmonary function testing, ed 9, St Louis, 2009, Elsevier.



Theory of Operation

- ETCO2 monitor approximates partial pressure of CO2 in arterial blood through end-tidal sampling of exhaled gas
- Infrared spectroscopy – Based on principle that molecules containing more than one element absorb infrared light in a characteristic manner
    - Can determine how much of a gas is present by measuring infrared radiation not absorbed

Microprocessor-Controlled Infrared CO2 Monitor



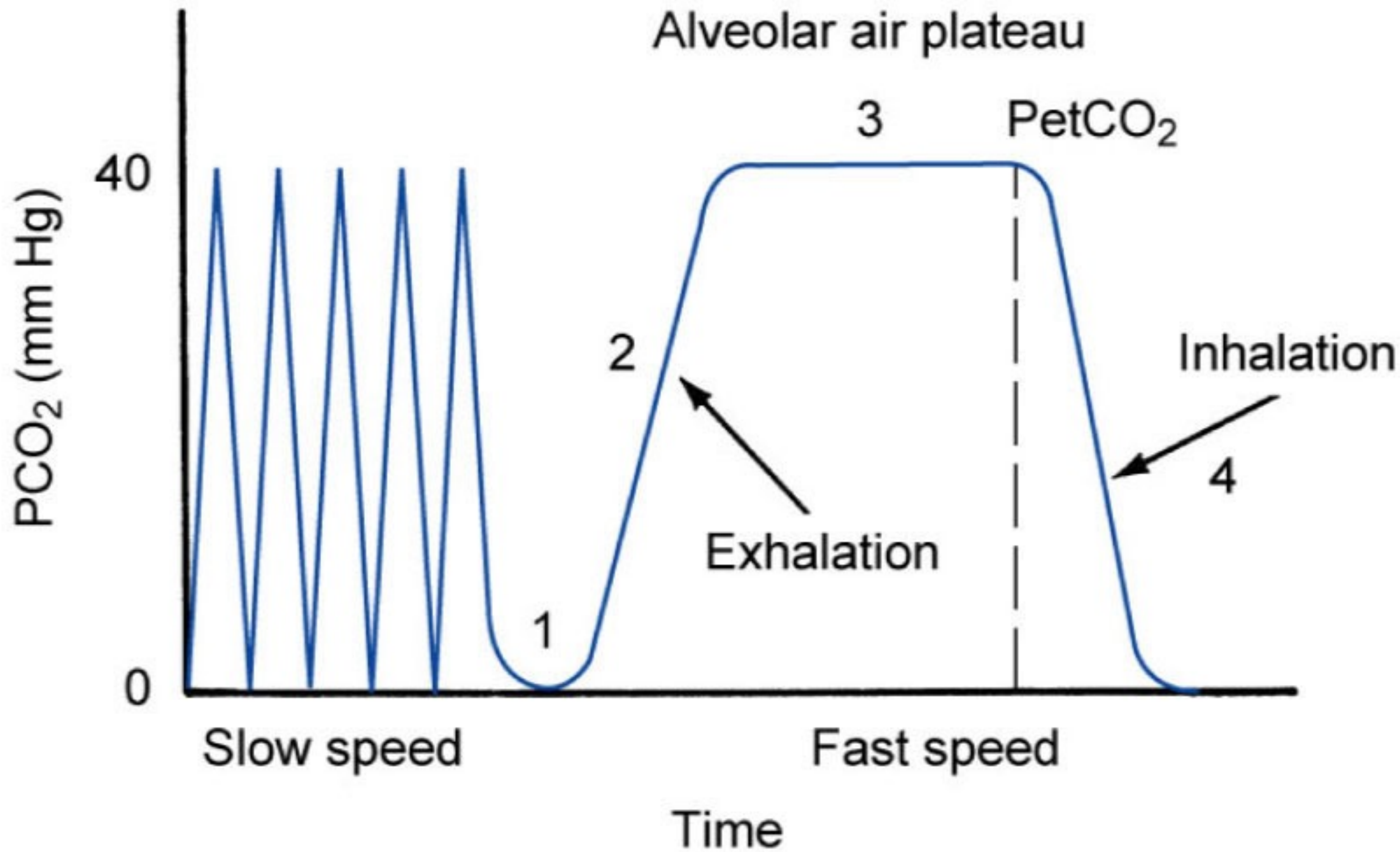
From Kacmarek RM, et al: Egan's fundamentals of respiratory care, ed 10, St Louis, 2013, Elsevier.

Double-Beam Infrared Capnometer Schematic

Theory of Operation

- 2 main methods of end-tidal monitoring:
  - Mainstream: Used when closed-system breathing circuit in use along with endotracheal or tracheostomy tube
  - Sidestream: For spontaneously breathing individuals
    - Typically, gas is sampled from nares through special nasal cannula
- Displaying ETCO2 data
  - Single-breath and time-based capnography
    - Typically, time-based is used in PSG
  - Tech needs to make sure secretions, moisture, or organic material don't build up in tubing

Capnogram



From Cairo JM: Pilbeam's mechanical ventilation: physiological and clinical applications, *ed 5, St Louis, 2012, Elsevier.*

Advantages and Limitations

- Signal is not always reliable for sidestream sampling
- Mouth breathing can also be problematic
- Increased ventilation-to-perfusion mismatch will show CO_2 above the normal 4-6 mm Hg increase
  - Seen with severe COPD patients for example
- Some modern $ETCO_2$ monitors include integrated pulse oximetry
  - Good for showing trends

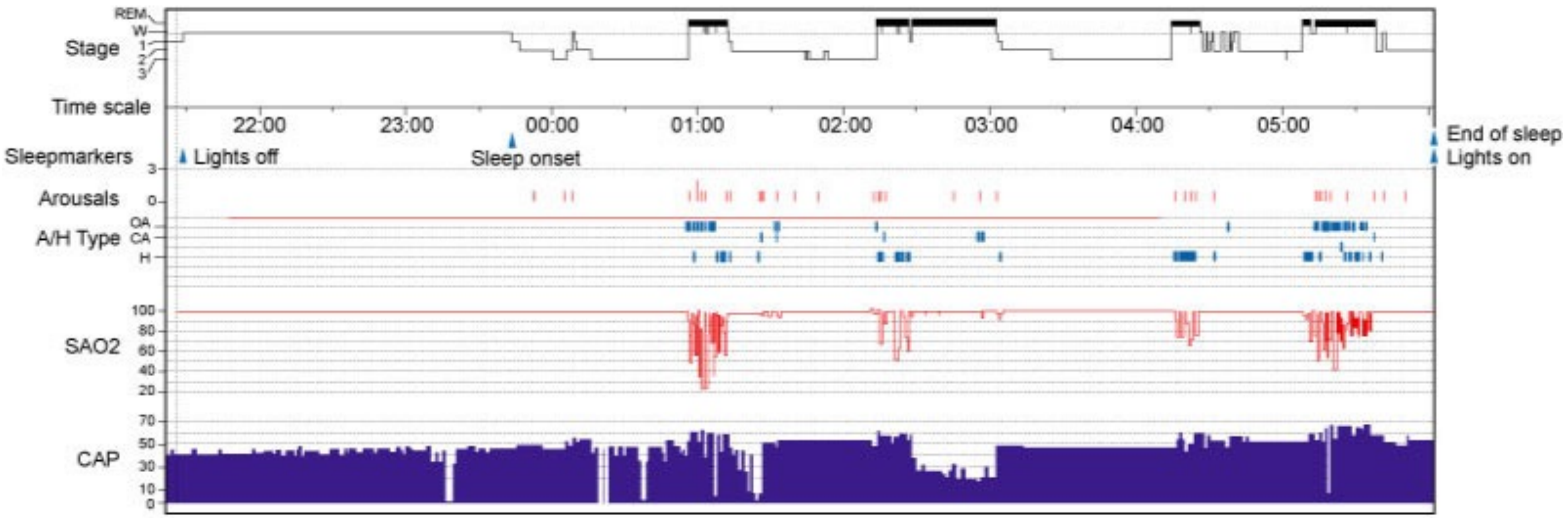
Capnometer with Integrated Pulse Oximetry

From Cairo JM: Pilbeam's mechanical ventilation: physiological and clinical applications, *ed 5, St Louis, 2012, Elsevier.*

Comparison of Obtained Values

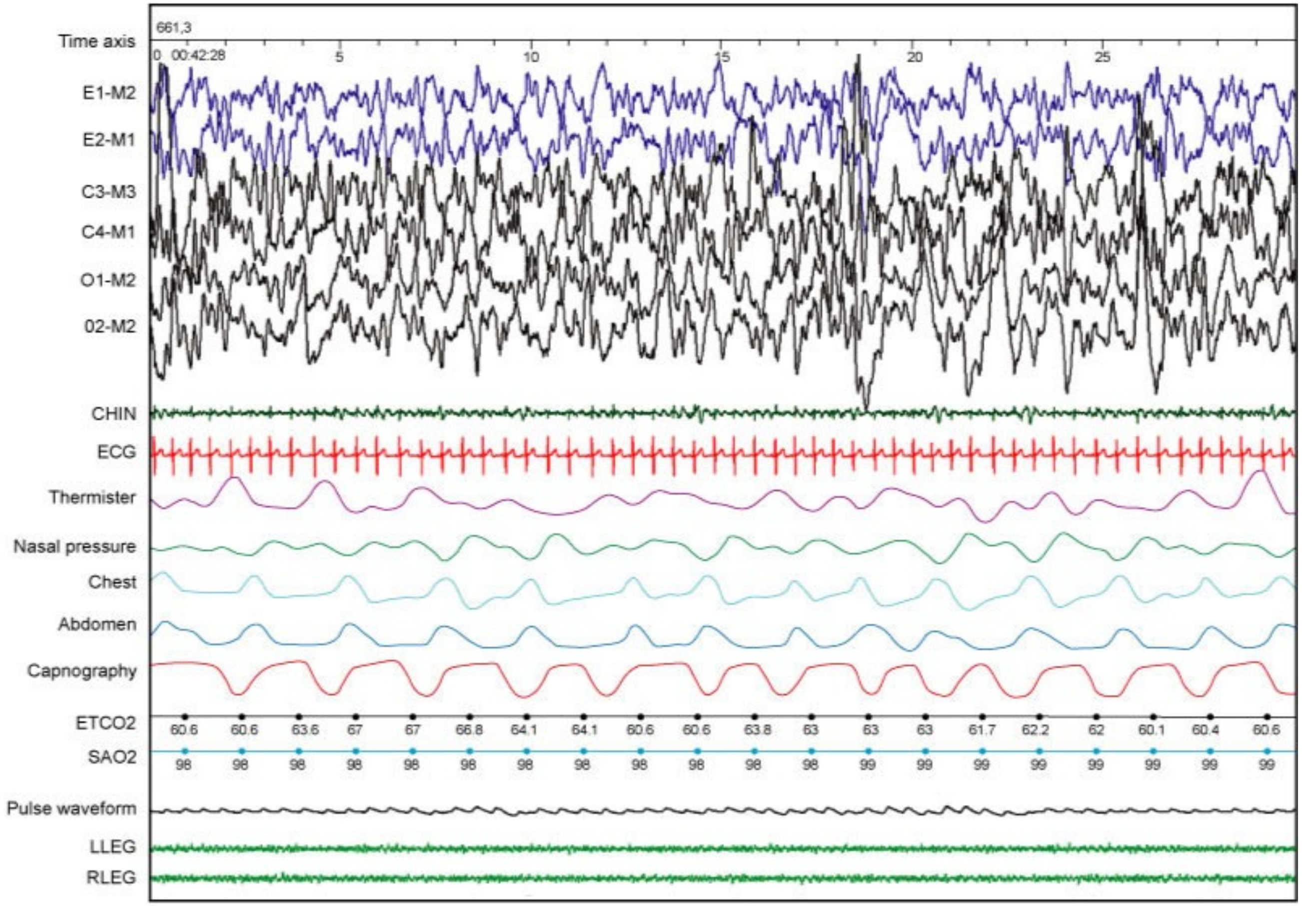
- Good correlation between arterial, end-tidal, and transcutaneous CO_2 values
  - But $ETCO_2$ tends to underestimate CO_2 values obtained from arterial blood
    - Normal gradient is 4-6 mm Hg
    - Not a good tool when precise values are required
    - Diminished when there is increased flow from PAP or supplemental O_2

Hypnogram of Trend Capnography Data



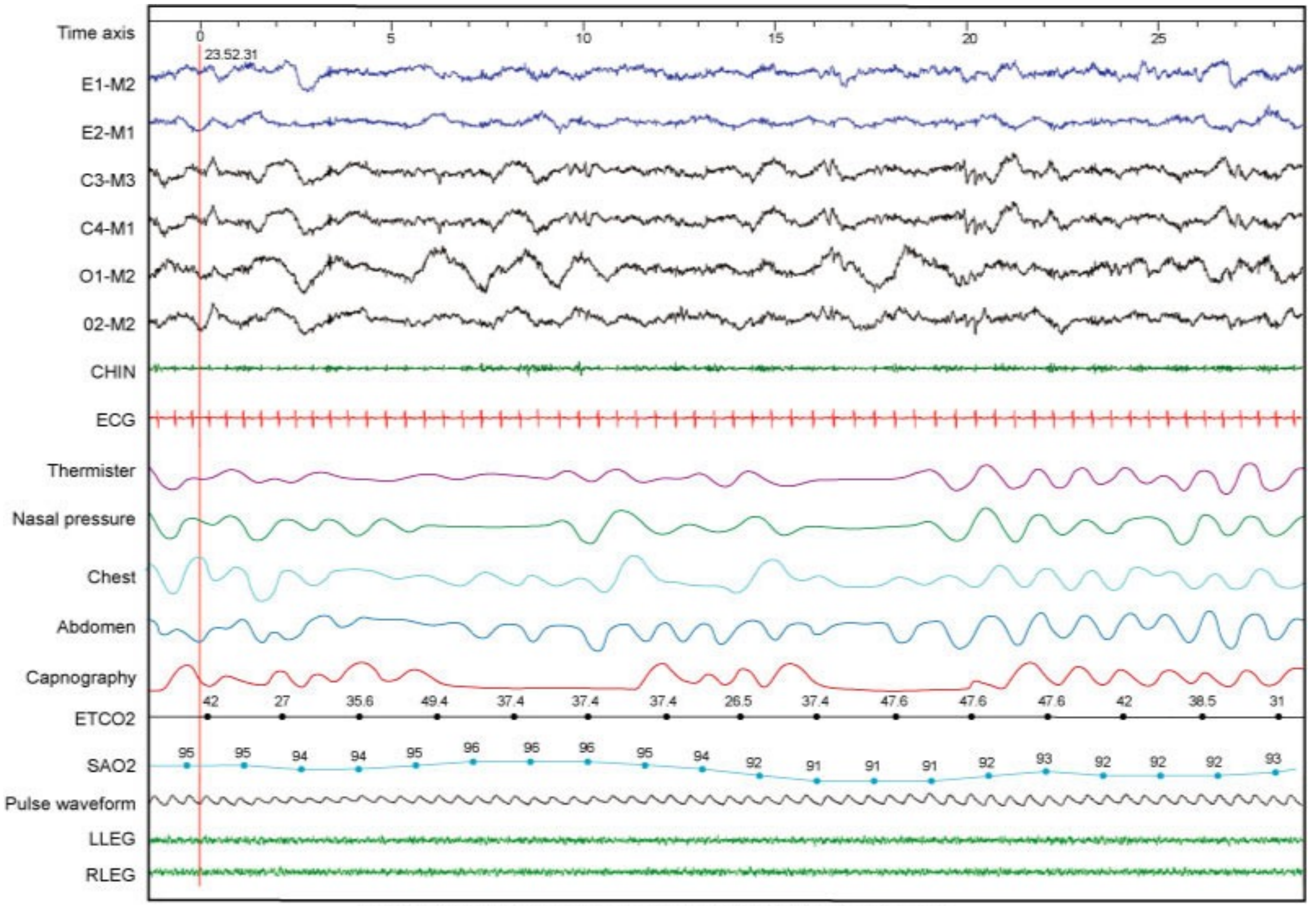
From Beck SE, Marcus CL: *Pediatric polysomnography*, Sleep Med Clin *4:393-406, 2009.*

7 Month Old with Meningomyelocele with Arnold-Chiari Malformation and Central Hypoventilation



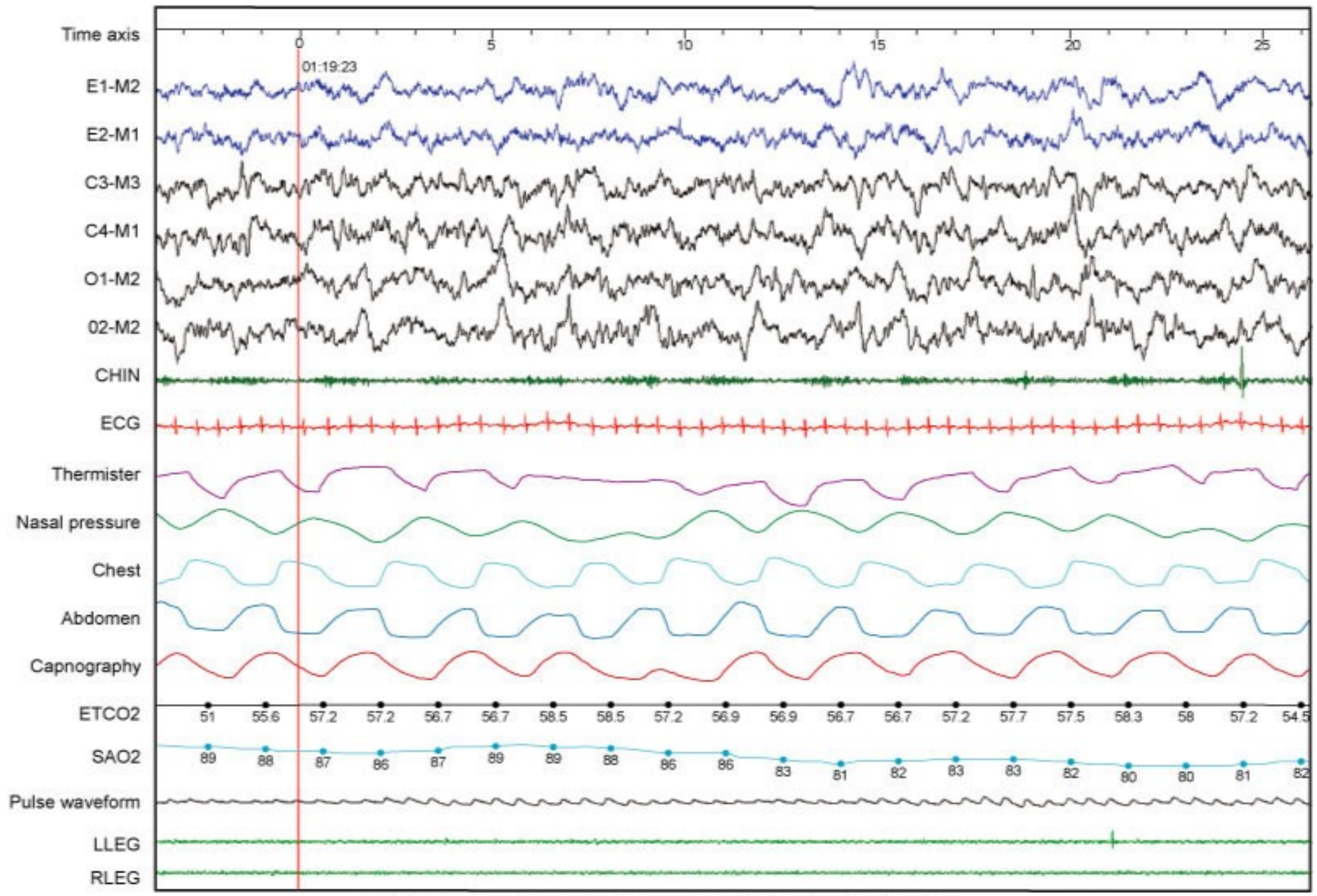
From Beck SE, Marcus CL: Pediatric polysomnography, Sleep Med Clin 4:393-406, 2009.

4 Month Old Infant with OSA



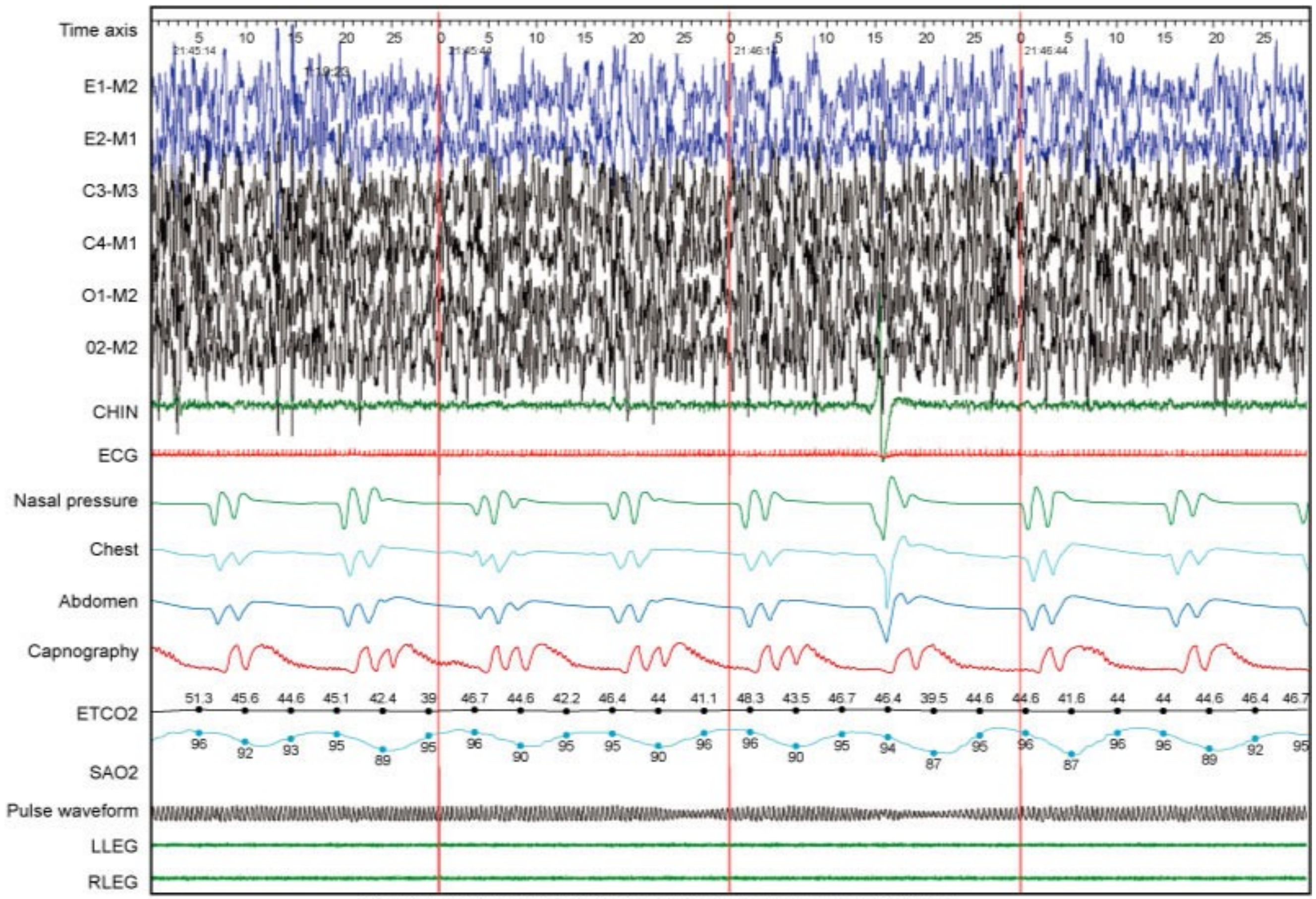
From Beck SE, Marcus CL: Pediatric polysomnography, Sleep Med Clin 4:393-406, 2009.

6 Year Old with Obstructive Hypoventilation and Elevated ETCO2 with Prolonged Desat



From Beck SE, Marcus CL: Pediatric polysomnography, Sleep Med Clin 4:393-406, 2009.

60-Second Epoch of Periodic Breathing



From Beck SE, Marcus CL: Pediatric polysomnography, Sleep Med Clin 4:393-406, 2009.

Contraindications, Precautions, and Infection Control

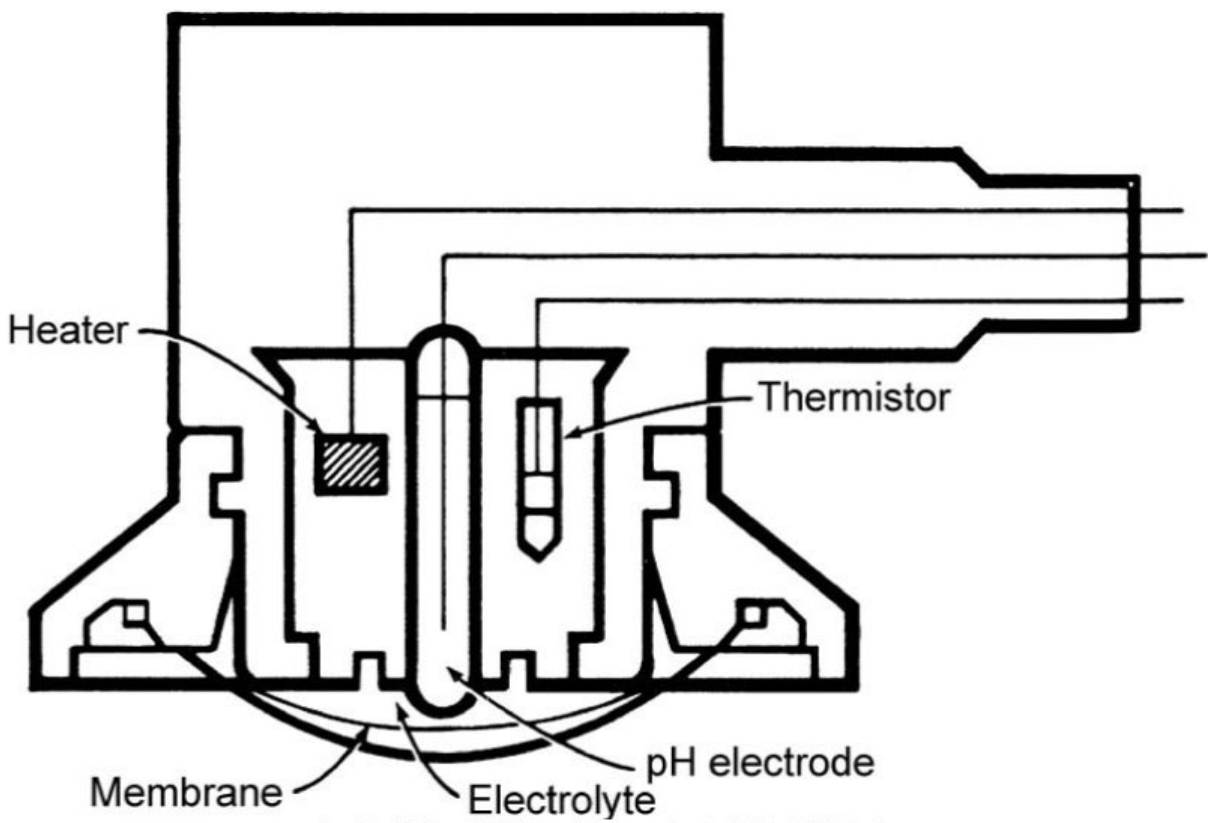
- Tech must carefully evaluate data obtained by sampling of end-tidal gas
- Gas sampling tubing and moisture filter are disposable, single-patient-use items
- No absolute contraindications for ETCO2

Transcutaneous Monitoring of O2 and CO2

- Approximates PaO2 and PaCO2 values by dilating capillary bed with heat and measuring capillary blood
- First mentioned by Severinghouse in 1960
  - First tcCO2 sensor not commercially available until 20 years later
  - First tcO2 sensor was used in 1967
  - Initially used in intensive care nursery
    - Sensors required frequent membrane changes and had to be moved to new site as often as every 2 hours
    - Monitor calibration required multiple times daily using gases of known low and high value

Transcutaneous Monitoring of O2 and CO2

- Typically only used in pediatrics
- Today's sensors can remain in one location as long as 8-12 hours
  - Sensors are small and lightweight



From Cairo JM, Pilbeam SP: Mosby's respiratory care equipment, ed 9, St Louis, 2011, Elsevier.

Advantages and Limitations

- Measured on surface of skin using modified blood gas electrodes
- Optimal location for sensor placement is area of high capillary density and minimal skin thickness
  - Earlobe, forearm, chest and abdomen
- Advantages:
  - No need to draw arterial blood
  - Ability to monitor and obtain reliable results during PAP or supplemental O2
- Disadvantage: Need for recording site to be warmed by sensor in order to enhance capillary vasodilation for increased accuracy
  - Can take 12-30 minutes for site to warm up

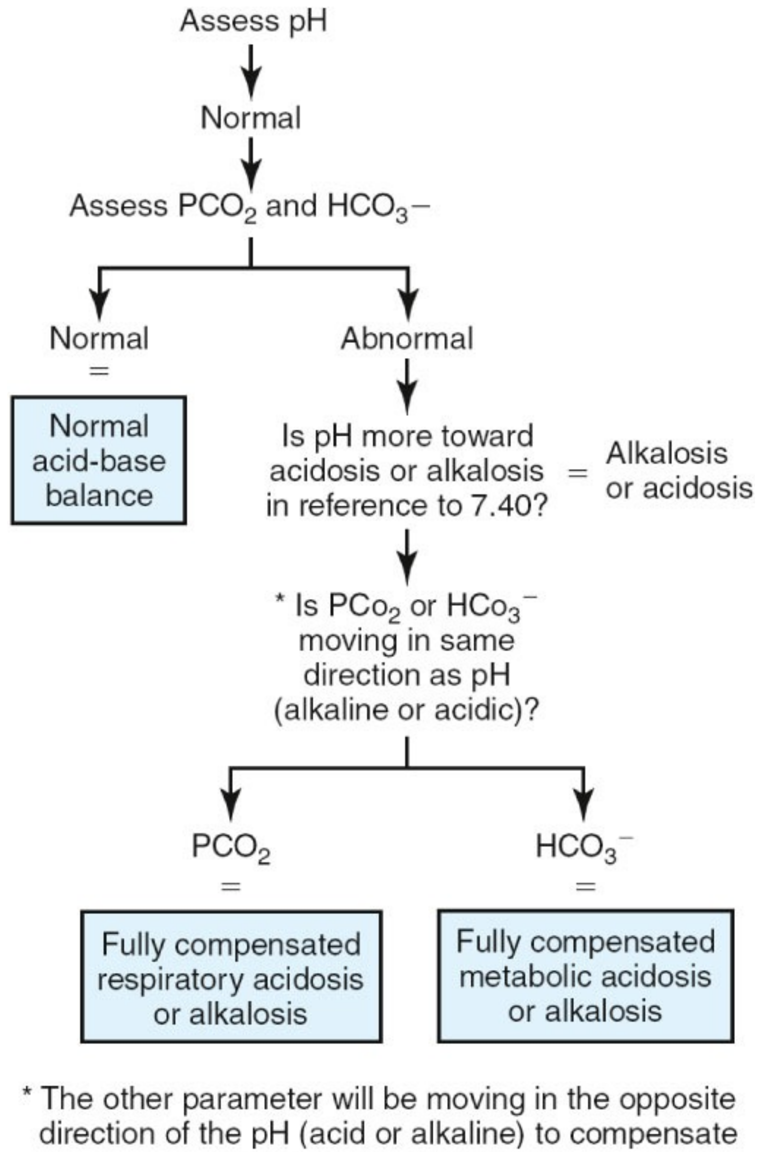
Comparison of Obtained Values

- $tcCO_2$ monitoring more reliable than tcO_2 monitoring
  - tcO_2 provides little value in a sleep study
- $tcCO_2$ tends to slightly overestimate $PaCO_2$
- $tcCO_2$ provides most reliable data for determining effects of therapy on ventilation throughout sleep study
  - Provides valid results when $ETCO_2$ may not be reliable

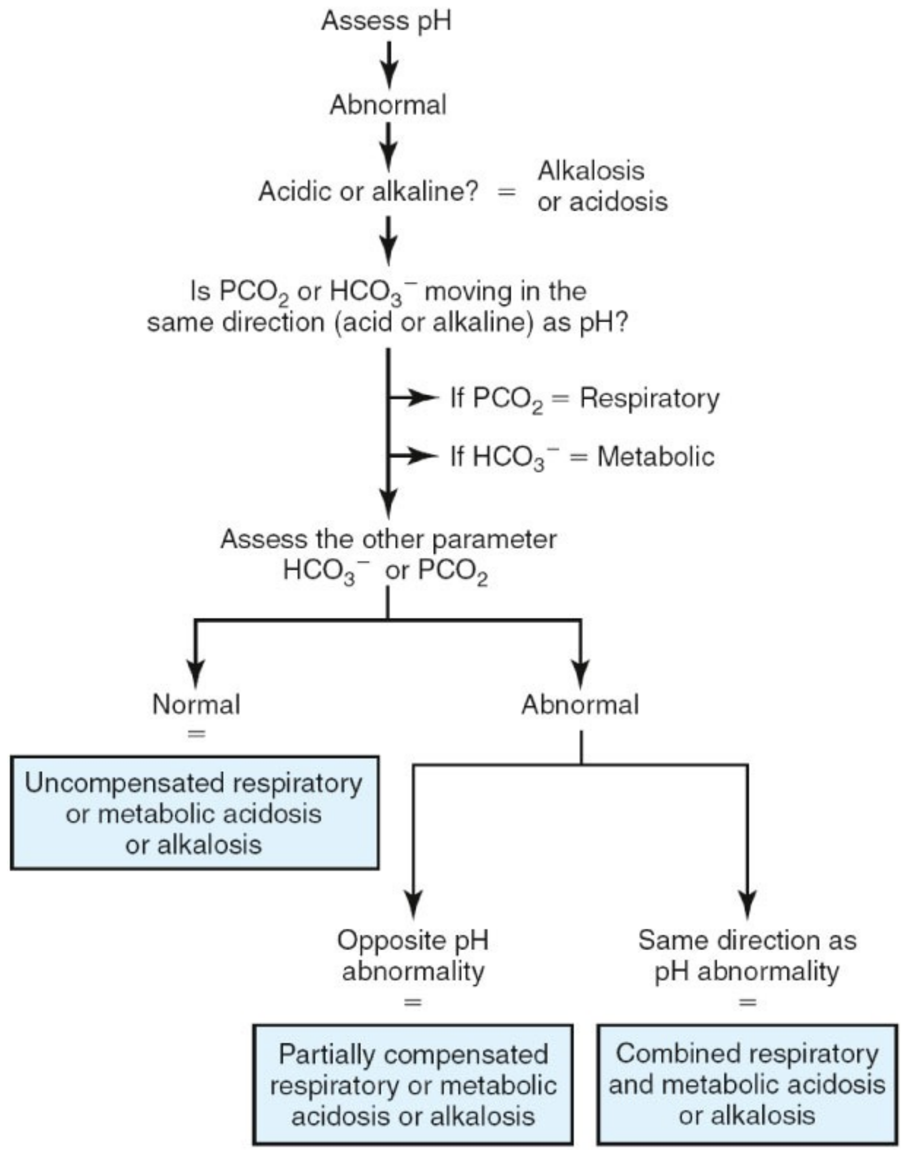
Contraindications, Precautions, and Infection Control

- No known absolute contraindications to tcCO2 monitoring
- Must be careful not to leave probe in one spot too long so as not to damage skin
- Integrity of skin must be assessed prior to placement of sensor
- Sensor, cable, and recorder should be cleaned and disinfected between each patient

Acid-Base with Normal pH



Acid-Base with Abnormal pH



Acid-Base Balance Quick Reference

	Acute	Partially Compensated	Fully Compensated
Respiratory Acidosis			
pH	↓	↓	Returns to normal
PaCO2	↑	↑	↑
HCO3-	Normal	↑	↑
Respiratory Alkalosis			
pH	↑	↑	Returns to normal
PaCO2	↓	↓	↓
HCO3-	Normal	↓	↓

Acid-Base Balance Quick Reference

	Acute	Partially Compensated	Fully Compensated
Metabolic Acidosis			
pH	↓	↓	Returns to normal
PaCO2	Normal	↓	↓
HCO3-	↓	↓	↓
Metabolic Alkalosis			
pH	↑	↑	Returns to normal
PaCO2	Normal	↑	↑
HCO3-	↑	↑	↑

Acid-Base Balance Quick Reference

	Combined Acidosis	Combined Alkalosis
pH	↓	↓
PaCO2	↑	↓
HCO3-	↓	↑