Cardiopulmonary Anatomy & Physiology

Essentials of Respiratory Care

Fifth Edition

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CHAPTER 7

Carbon Dioxide Transport and Acid-Base Balance

Carbon Dioxide Transport

- In plasma:
  - Carbamino compound (bound to protein)
  - Bicarbonate
  - Dissolved CO_2

CO_2 Is Converted to HCO_3

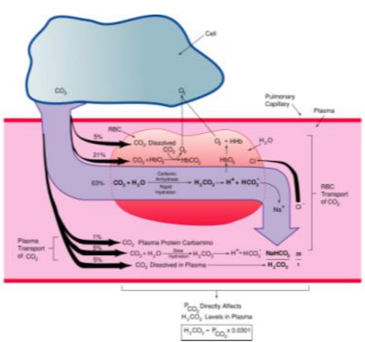

Fig. 7-1. How CO_2 is converted to HCO_3 at the tissue sites. Most of the CO_2 that is produced at the tissue cells is carried to the lungs in the form of HCO_3.

Carbon Dioxide Transport

- In red blood cells:
  - Dissolved CO_2
  - Carbamino-Hb
  - Bicarbonate

CARBON DIOXIDE ELIMINATION AT THE LUNGS

How HCO_3 Is Transformed into CO_2

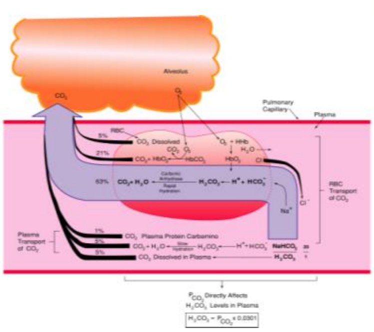

Fig. 7-2. How HCO_3 is transformed back into CO_2 and eliminated in the alveoli.

Carbon Dioxide (CO_2) Transport Mechanisms

Table 7-1

CO_2 Transport Mechanisms	Approx. % of Total CO_2 Transported to the Lungs	Approx. Quantity of Total CO_2 to the Lungs (ML/MIN)
IN PLASMA		
Carbamino compound	1	2
Bicarbonate	5	10
Dissolved CO_2	5	10
IN RED BLOOD CELLS		
Dissolved CO_2	5	10
Carbamino-Hb	21	42
Bicarbonate	63	126
Total	100	200

Carbon Dioxide Dissociation Curve

- Similar to the oxygen dissociation curve, the loading and unloading of CO_2 in the blood can be illustrated in graphic form.

Carbon Dioxide Dissociation Curve

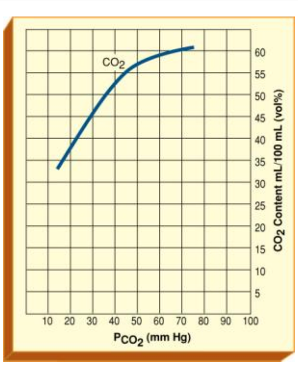

Fig. 7-3. Carbon dioxide dissociation curve.

Carbon Dioxide Dissociation Curve

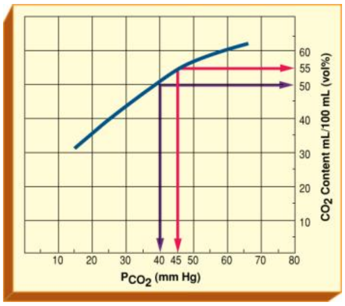

Fig. 7-4. Carbon dioxide dissociation curve. An increase in the PCO_2 from 40 mm Hg to 46 mm Hg raise the CO_2 content by about 5 vol.%. PCO_2 changes have a greater effect on CO_2 content levels than PO_2 changes on O_2 levels.

Carbon Dioxide Dissociation Curve

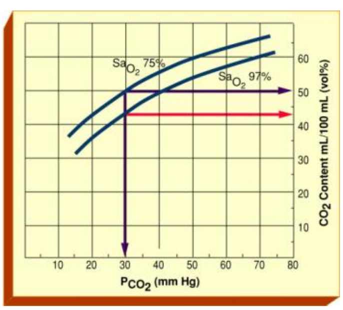

Fig. 7-5. Carbon dioxide dissociation curve at two different oxygen/hemoglobin saturation levels (SaO_2 of 97% and 75%). When the saturation of O_2 increases in the blood, the CO_2 content decreases at any given PCO_2. This is known as the Haldane effect.

Carbon Dioxide Dissociation Curve

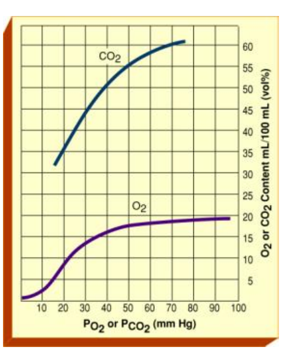

Fig. 7-6. Comparison of the oxygen and carbon dioxide dissociation curves in terms of partial pressure, content, and shape.

ACID-BASE BALANCE AND REGULATION

Acid-Base Balance and Regulation

- Nearly all biochemical reactions in the body are influenced by the acid-base balance of their fluid environment
- Normal arterial pH range is 7.34 to 7.45

Acid-Base Balance and Regulation

- pH > 7.45 = alkalosis
- pH < 7.35 = acidosis

Acid-Base Balance and Regulation

- Most H^+ ions in the body originate from:
  1. Breakdown of phosphorous-containing proteins (phosphoric acid)
  2. Anaerobic metabolism of glucose (lactic acid)
  3. Metabolism of body fats (fatty and ketone acids)
  4. Transport of CO_2 in the blood as HCO_3^- liberates H^+ ions

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H^+ and HCO_3

- Under normal conditions, both the H^+ and HCO_3^- ion concentrations in the blood are regulated by the following three major systems:
  - Chemical buffer system
  - Respiratory system
  - Renal system

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The Chemical Buffer System

- Responds within a fraction of a second to resist pH changes
  - Called the first line of defense

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The Chemical Buffer System

- System is composed of:
  1. Carbonic acid-bicarbonate buffer system
  2. Phosphate buffer system
  3. Protein buffer system

The Respiratory System

- Acts within one to three minutes by increasing or decreasing the breathing depth and rate to offset acidosis or alkalosis, respectively.

The Renal System

- Body's most effective acid-base balance monitor and regulator
- Renal system requires a day or more to correct abnormal pH concentrations

Acid-Base Balance

- Note:
  - To fully appreciate acid-base balance, and how it is normally regulated, a fundamental understanding of acids and bases, and their influences on pH, is essential.

THE BASIC PRINCIPLES OF ACID-BASE REACTIONS AND pH

Acids and Bases

- Similar to salts, acids and bases are electrolytes
- Thus, both acids and bases can:
  - Ionize and dissociate in water
  - Conduct an electrical current

Acids

- Acids are sour tasting, can react (dissolve) with many metals, and can “burn” a hole through clothing
- An acid is a substance that releases hydrogen ions [H^+] in measurable amounts

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Acids

- Because a hydrogen ion is only a hydrogen nucleus proton, acids are defined as proton donors.
- Thus, when acids dissolve in a water solution, they release hydrogen ions (protons) and anions.

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Acids

- Acidity of a solution is directly related to the concentration of protons.
- Anions have little or no effect on the acidity.
- Thus, the acidity of a solution reflects only the free hydrogen ions, not those bound to anions.

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Acids

- For example, *hydrochloric acid* (HCl), the acid found in the stomach and works to aid digestion, dissociates into a proton and a chloride ion:

$$HCl \;\Delta\; H^+ \quad Cl^-$$

proton anion

Acids

- Other acids in the body include acetic acid ($HC_2H_3O_2$), often abbreviated as [HAc], and carbonic acid (H_2CO_3)
- Molecular formula for common acids is easy to identify because it begins with the hydrogen ion

Strong Acids

- Acidity of a solution reflects only the free hydrogen ions
  - Not the hydrogen ions still combined with anions.
- Thus, strong acids, which dissociate completely (i.e., they liberate all the H^+) and irreversibly in water, dramatically change the pH of the solution.

Strong Acids

- For example, if 100 hydrochloric (HCl) acid molecules were placed in 1 mL of water, the hydrochloric acid would dissociate into 100 H^+ and 100 Cl^- ions.
- There would be no undissociated hydrochloric acid molecules in the solution.

Weak Acids

- Do not dissociate completely in a solution and have a much smaller effect on pH
- Although weak acids have a relatively small effect on changing pH levels, they have a very important role in resisting sudden pH changes.

Weak Acids

- Examples of weak acids are carbonic acid (H_2CO_3) and acetic acid ($HC_2H_3O_2$)
- If 100 acetic acid molecules were placed in 1 mL of water, the following reaction would occur:

$$100\ HC_2H_3O_2\ \Delta\ 90\ HC_2H_3O_2 + \underset{\text{(Hydrogen ions)}}{10\ H^+} + \underset{\text{(Acetate ions)}}{10\ C_2H_3O_2^-}$$

Weak Acids

- Because undissociated acids do not alter the pH, the acidic solution will not be as acidic as the HCl solution discussed above
- The dissociation of acetic acid can be written as follows:

$$HC_2H_3O_2 \rightleftharpoons H^+ + C_2H_3O_2^-$$

Weak Acids

- Using this equation, it can be seen that:
  - When H^+ (released by a strong acid) is added to the acetic acid solution
  - Equilibrium moves to the left as some of the additional H^+ bonds with $C_2H_3O_2^-$ to form $HC_2H_3O_2$

Weak Acids

- On the other hand, when a strong base is added to the solution (adding additional OH^- and causing the pH to increase), the equilibrium shifts to the right
- This occurs because the additional OH^- consumes the H^+

Weak Acids

- Cause more $HC_2H_3O_2$ molecules to dissociate and replenish the H^+
- Weak acids play a very important role in the chemical buffer systems of the human body

Bases

- Bases are proton acceptors
- Bases taste bitter and feel slippery
- A base is a substance that takes up hydrogen ions [H^+] in measurable amounts

Bases

- Common inorganic bases include the hydroxides
  - Magnesium hydroxide (milk or magnesia) and sodium hydroxide (lye)
- Similar to acids, when dissolved in water, hydroxides dissociate into hydroxide ions ($OH^–$) and cations

Bases

- For example, ionization of sodium hydroxide (NaOH) results in a hydroxide ion and a sodium ion
- Liberated hydroxide ion then bonds, or accepts, a proton present in the solution
- Reaction produces water and, at the same time, decreases the acidity [H^+ concentration] of the solution

Bases

- The solution:

$$NaOH \;\Delta\; \underset{\text{cation}}{Na^+} + \underset{\text{hydroxide ion}}{OH^-}$$

- And then:

$$OH^- + H^+ \;\Delta\; \underset{\text{water}}{H_2O}$$

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Bases

- Bicarbonate ion (HCO_3^-) is an important base in the body and is especially abundant in the blood

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Bases

- Ammonia (NH_3), a natural waste product of protein breakdown, is also a base
- Ammonia has a pair of unshared electrons that strongly attract protons
- When accepting a proton, ammonia becomes an ammonium ion:

$$NH_3 + H^+ \rightleftharpoons \underbrace{NH_4^+}_{\text{ammonium ion}}$$

STRONG AND WEAK BASES

Strong Bases

- Remember, bases are proton acceptors
- Strong bases dissociate easily in water and quickly tie up H^+
  - Hydroxides

Weak Bases

- In contrast, weak bases:
  - Sodium bicarbonate or baking soda
  - Dissociate incompletely and reversibly and are slower to accept protons
- Because sodium bicarbonate accepts a relatively small amount of protons
  - Its released bicarbonate ion is described as a weak base

pH: Acid-Base Concentration

- As the concentration of hydrogen ions in a solution increase:
  - The more acidic the solution becomes
- As the level of hydroxide ions increases:
  - The more basic, or alkaline, the solution becomes

pH: Acid-Base Concentration

- Clinically, the concentration of hydrogen ions in the body is measured in units called *pH units*
- pH scale runs from 0 to 14 and is logarithmic

pH: Acid-Base Concentration

- Each successive unit change in pH represents a tenfold change in hydrogen ion concentration

pH: Acid-Base Concentration

- pH of a solution, therefore, is defined as the negative logarithm, to the base 10, of the hydrogen ion concentration $[H^+]$ in moles per liter, or $-\log H^+$:

$$pH = -\log_{10} [H^+]$$

pH: Acid-Base Concentration

- When the pH is 7 ($H^+ = 10^{-7}$ mol/liter)
  - Number of hydrogen ions precisely equals the number of hydroxide ions (OH^-)
- And the solution is neutral
  - Neither acidic or basic

pH: Acid-Base Concentration

- Pure water has a neutral pH of 7, or 10^{-7} mol/liter (0.0000001 mol/liter) of hydrogen ions.
- A solution with a pH below 7, is acidic
  - There are more hydrogen ions than hydroxide ions

pH: Acid-Base Concentration

- For example, a solution with a pH of 6 has 10 times more hydrogen ions than a solution with a pH of 7

pH: Acid-Base Concentration

- A solution with a pH greater than 7, is alkaline
  - Hydroxide ions outnumber the hydrogen ions
- For example, a solution with a pH of 8 has 10 times more hydroxide ions than a solution with a pH of 7

pH: Acid-Base Concentration

- Thus, as the hydrogen ion concentration increases
  - Hydroxide ion concentration falls, and vice versa.

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pH Values of Representative Substances

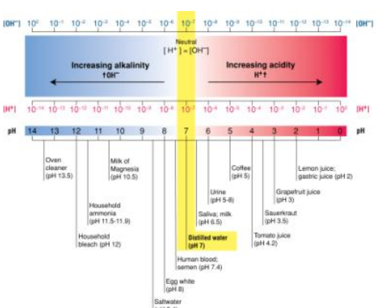

Figure 7-7 The pH values of representative substances. The pH scale represents the number of hydrogen ions in a substance. The concentration of hydrogen ions (H^+) and the corresponding hydroxyl concentration (OH^-) for each representative substance is also provided. Note that when the pH is 7.0, the amount of H^+ and OH^- are equal and the solution is neutral.

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Chemical Buffer Systems and Acid-Base Balance

- Chemical buffers resist pH changes and are the body's first line of defense.
- Ability of an acid-base mixture to resist sudden changes in pH is called its buffer action.

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Chemical Buffer Systems and Acid-Base Balance

- Tissue cells and vital organs of the body are extremely sensitive to even the slightest change in the pH environment

Chemical Buffer Systems and Acid-Base Balance

- In high concentrations, both acids and bases can be extremely damaging to living cells
  - Essentially every biological process within the body is disrupted

Chemical Buffer Systems and Acid-Base Balance

- Buffers work against sudden and large changes in the pH of body fluids by
  1. Releasing hydrogen ions (acting as acids) when the pH increases, and
  2. Binding hydrogen ions (acting as bases) when the pH decreases.

Chemical Buffer Systems and Acid-Base Balance

- Three major chemical buffer systems in the body are the:
  - Carbonic acid-bicarbonate buffer system
  - Phosphate buffer system
  - Protein buffer system

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- The carbonic acid-bicarbonate buffer system
  - Plays an extremely important role in maintaining pH homeostasis of the blood.

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- Carbonic acid (H_2CO_3) dissociates reversibly and releases bicarbonate ions (HCO_3^-) and protons (H^+) as follows:

Response to an increase in pH

$$\underset{\substack{H^+\ \text{donor} \\ \text{(weak acid)}}}{H_2CO_3} \underset{\text{Response to a decrease in pH}}{\rightleftarrows} \underset{\substack{H^+\ \text{acceptor} \\ \text{(weak proton)}}}{HCO_3^-} + \underset{\text{proton}}{H^+}$$

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- Under normal conditions, the ratio between the HCO_3^- and H_2CO_3 in the blood is 20:1
  - See Figure 7-1

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- Chemical equilibrium between carbonic acid (weak acid) and bicarbonate ion (weak base) works to resist sudden changes in blood pH.

How CO_2 Is Converted to HCO_3

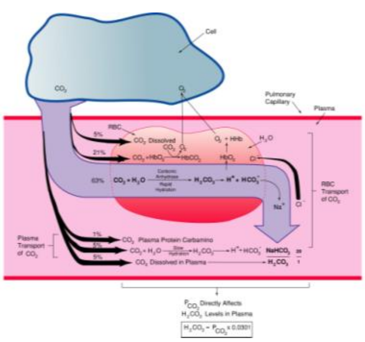

Fig. 7-1. How CO_2 is converted to HCO_3 at the tissue sites. Most of the CO_2 that is produced at the tissue cells is carried to the lungs in the form of HCO_3^-.

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- For example, when the blood pH increases (i.e., becomes more alkaline from the addition of a strong base), the equilibrium shifts to the right.
- A right shift forces more carbonic acid to dissociate, which in turn causes the pH to decrease.

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- In contrast, when the blood pH decreases (i.e., becomes more acidic from the addition of a strong acid), the equilibrium moves to the left.
- A left shift forces more bicarbonate to bind with protons.

Carbonic Acid-Bicarbonate Buffer System and Acid-Base Balance

- Carbonic acid-bicarbonate buffer system converts:
  1. Strong bases to a weak base (bicarbonate ion), and
  2. Strong acids to a weak acid (carbonic acid)
- Blood pH changes are much less than they would be if this buffering system did not exist.

The Henderson-Hasselbalch Equation (H-H)

- H-H equation mathematically illustrates how the pH of a solution is influenced by the HCO_3^- to H_2CO_3 ratio
  - The base to acid ratio

The Henderson-Hasselbalch Equation (H-H)

- H-H equation is written as follows:

$$pH = pK + \log \frac{[HCO_3^-]\text{ (base)}}{[H_2CO_3]\text{ (acid)}}$$

- pK is derived from the dissociation constant of the acid portion of the buffer combination
- pK is 6:1 and, under normal conditions, the HCO_3^- to H_2CO_3 ratio is 20:1

The Henderson-Hasselbalch Equation (H-H)

- Clinically, the dissolved CO_2 (PCO_2 x 0.03) can be used for the denominator of the H-H equations, instead of the H_2CO_3
- This is possible since the dissolved carbon dioxide is in equilibrium with, and directly proportional to, the blood $[H_2CO_3]$

The Henderson-Hasselbalch Equation (H-H)

- Thus, the H-H equation can be written as follows:

$$pH = pK + \log \frac{[HCO_3^-]}{[PCO_2 \times 0.03]}$$

H-H Equation Applied During Normal Conditions

- When the HCO_3^- is 24 mEq/L, and the $PaCO_2$ is 40 mm Hg, the base to acid ratio is 20:1 and the pH is 7.4 (normal).
- H-H equation confirms the 20:1 ratio and pH of 7.4 as follows:

H-H Equation Applied During Normal Conditions

$$pH = pK + \log \frac{[HCO_3^-]}{[PCO_2 \times 0.03]}$$

$$= 6.1 + \log \frac{24 \text{ mEq/L}}{(40 \times 0.03)}$$

$$= 6.1 + \log \frac{24 \text{ mEq/L}}{(1.2 \text{ mEq/L})}$$

$$= 6.1 + \log \frac{20}{1} \quad \text{(20:1 ratio)}$$

$$= 6.1 + 1.3$$

$$= 7.4$$

H-H Equation Applied During Abnormal Conditions

- When the HCO^{3-} is 29 mEq/L, and the $PaCO_2$ is 80 mm Hg, the base to acid ratio decreases to 12:1 and the pH is 7.18 (acidic)
- H-H equation confirms the 12:1 ratio and the pH of 7.18 as follows:

H-H Equation Applied During Abnormal Conditions

$$pH = pK + \log \frac{[HCO_3^-]}{[PCO_2 \times 0.03]}$$

$$= 6.1 + \log \frac{29 \text{ mEq/L}}{(80 \times 0.03)}$$

$$= 6.1 + \log \frac{29 \text{ mEq/L}}{(2.4 \text{ mEq/L})}$$

$$= 6.1 + \log \frac{12}{1} \quad \text{(12:1 ratio)}$$

$$= 6.1 + 1.08$$

$$= 7.18$$

H-H Equation Applied During Abnormal Conditions

- In contrast, when the HCO_3^- is 20 mEq/L, and the $PaCO_2$ is 20 mm Hg, the base to acid ratio increases to 33:1 and the pH is 7.62 (alkalotic)
- H-H equation confirms the 33:1 ratio and the pH of 7.62 as follows:

H-H Equation Applied During Abnormal Conditions

$$\begin{aligned}
pH &= pK + \log \frac{[HCO_3^-]}{[PCO_2 \times 0.03]} \\
&= 6.1 + \log \frac{20 \text{ mEq/L}}{(20 \times 0.03)} \\
&= 6.1 + \log \frac{20 \text{ mEq/L}}{(0.6 \text{ mEq/L})} \\
&= 6.1 + \log \frac{33}{1} \quad \text{(33:1 ratio)} \\
&= 6.1 + 1.52 \\
&= 7.62
\end{aligned}$$

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Clinical Application of H-H Equation

- Clinically, the H-H equation can be used to calculate the pH, $[HCO_3^-]$, or PCO_2 when any two of these three variables are known. $[HCO_3^-]$ is solved as follows:

$$[HCO_3^-] = \text{antilog } (7.40 - 6.1) \times (PCO_2 \times 0.03)$$

- PCO_2 is determined as follows:

$$PCO_2 = \frac{[HCO_3^-]}{(\text{antilog } [pH - 6.1] \times 0.03)}$$

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Clinical Application of H-H Equation

- H-H equation may be helpful in cross checking the validity of the blood gas reports when the pH, PCO_2, and $[HCO_3^-]$ values appear out of line.
- It may also be useful in estimating what changes to expect when any one of the H-H equation components is altered.

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Clinical Application of H-H Equation

- For example, consider the case example that follows:

Case

- A mechanically ventilated patient has a pH of 7.54, a $PaCO_2$ of 26 mm Hg, and a HCO_3^- of 22 mEq/L.
- The physician asks the respiratory practitioner to adjust the patient's $PaCO_2$ to a level that will decrease the pH to 7.45.

Case

- Using the H-H equation, the $PaCO_2$ change needed to decrease the pH to 7.45 can be estimated as follows:

Case

$$PCO_2 = \frac{[HCO_3^-]}{(\text{antilog } [pH - 6.1] \times 0.03)}$$

$$= \frac{22}{\text{antilog } (7.45 - 6.1) \times 0.03}$$

Case

$$= \frac{22}{\text{antilog } (1.35) \times 0.03}$$

$$= \frac{22}{22.38 \times 0.03}$$

$$= \frac{22}{0.67}$$

= 32.8 or 33 mm Hg

Clinical Application of H-H Equation

- Thus, increasing the $PaCO_2$ to about 33 mm Hg should move the patient's pH level close to 7.45.
- In this case, the respiratory practitioner would begin by either decreasing the tidal volume, or the respiratory rate, on the mechanical ventilator.

Clinical Application of H-H Equation

- After the ventilator changes are made
  - Another arterial blood gas should be obtained in about 20 minutes
- pH and $PaCO_2$ should be reevaluated
  - Followed by appropriate ventilator adjustments if necessary

Phosphate Buffer System and Acid-Base Balance

- Function of the phosphate buffer system is almost identical to that of the carbonic acid-bicarbonate buffer system

Phosphate Buffer System and Acid-Base Balance

- Primary components of the phosphate buffer system are the:
  - Sodium salts of dihydrogen phosphate ($H_2PO_4^-$), and
  - Monohydrogen phosphate (HPO_4^{2-})

Phosphate Buffer System and Acid-Base Balance

- NaH_2PO_4 is a weak acid
- Na_2HPO_4, which has one less hydrogen atom, is a weak base

Phosphate Buffer System and Acid-Base Balance

- When H^+ ions are released by a strong acid, the phosphate buffer system works to inactivate the acidic effects of the H^+ as follows:

$$\underset{\text{strong acid}}{HCl} + \underset{\text{weak base}}{Na_2HPO_4} \;\Delta\; \underset{\text{weak acid}}{NaH_2PO_4} + \underset{\text{salt}}{NaCl}$$

Phosphate Buffer System and Acid-Base Balance

- On the other hand, strong bases are converted to weak bases as follows:

$$\underset{\text{strong base}}{NaOH} + \underset{\text{weak acd}}{NaH_2PO_4} \;\Delta\; \underset{\text{weak base}}{Na_2HPO_4} + \underset{\text{water}}{H_2O}$$

Phosphate Buffer System and Acid-Base Balance

- Phosphate buffer system is not an effective buffer for blood plasma
- It is an effective buffer system in urine and in intracellular fluid where the phosphate levels are typically greater.

Phosphate Buffer System and Acid-Base Balance

- Body's most abundant and influential supply of buffers is the protein buffer system
- Its buffers are found in the proteins in the plasma and cells

Phosphate Buffer System and Acid-Base Balance

- In fact, about 75 percent of the buffering power of body fluids is found in the intracellular proteins.

Phosphate Buffer System and Acid-Base Balance

- Proteins are polymers of amino acids
- Some have exposed groups of atoms known as organic acid (carboxyl) groups (—COOH), which dissociate and liberate H^+ in response to a rising pH:

$$R^* \text{—COOH} \,\Delta\, R \text{—COO}^- + H^+$$

*R represents the entire organic molecule, which is composed of many atoms

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Phosphate Buffer System and Acid-Base Balance

- In contrast, other amino acids consist of exposed groups that can function as bases and accept H^+.
- For example, an exposed —NH_2 group can bond with hydrogen ions to form —NH_3^+:

$$R \text{—}NH_2 + H+ \,\Delta\, R \text{—}NH_3^+$$

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Phosphate Buffer System and Acid-Base Balance

- Because this reaction ties up free hydrogen ions, it prevents the solution from becoming too acidic.
- In addition, a single protein molecule can function as either an acid or a base relative to its pH environment.

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Phosphate Buffer System and Acid-Base Balance

- Protein molecules that have a reversible ability are called amphoteric molecules

Phosphate Buffer System and Acid-Base Balance

- Hemoglobin in red blood cells is a good example of a protein the works as an intracellular buffer
- As discussed earlier, CO_2 released at the tissue cells quickly forms H_2CO_3, and then dissociates into H^+ and HCO_3^- ions
- See Figure 7-1

How CO_2 Is Converted to HCO_3^-

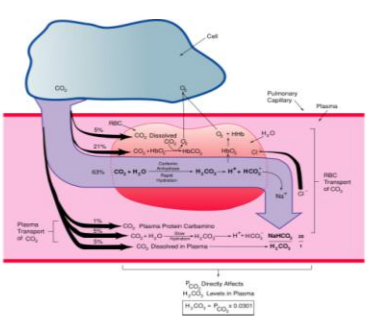

Fig. 7-1. How CO_2 is converted to HCO_3^- at the tissue sites. Most of the CO_2 that is produced at the tissue cells is carried to the lungs in the form of HCO_3^-.

Phosphate Buffer System and Acid-Base Balance

- At the same time, the hemoglobin is unloading oxygen at the tissue sites and becoming reduced hemoglobin.
- Because reduced hemoglobin carries a negative charge
  - Free H^+ ions quickly bond to the hemoglobin anions

Phosphate Buffer System and Acid-Base Balance

- This action reduces the acidic effects of the H^+ on the pH
- In essence, the H_2CO_3, which is a weak acid, is buffered by an even weaker acid—the hemoglobin protein

The Respiratory System and Acid-Base Balance

- Respiratory system does not respond as fast as the chemical buffer systems.
- However, it has up to two times the buffering power of all of the chemical buffer systems combined.

The Respiratory System and Acid-Base Balance

- CO_2 produced by the tissue cells enters the red blood cells and is converted to HCO_3^- ions as follows:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^-$$

The Respiratory System and Acid-Base Balance

- The first set of double arrows illustrates a reversible equilibrium between the dissolved carbon dioxide and the water on the left
  - And carbonic acid on the right

The Respiratory System and Acid-Base Balance

- The second set of arrows shows a reversible equilibrium between carbonic acid on the left and hydrogen and bicarbonate ions on the right

The Respiratory System and Acid-Base Balance

- Because of this relationship, an increase in any of these chemicals causes a shift in the opposite direction
- Note also that the right side of this equation is the same as that for the carbonic acid-bicarbonate buffer system

The Respiratory System and Acid-Base Balance

- Under normal conditions, the volume of CO_2 eliminated at the lungs is equal to the amount of CO_2 produced at the tissues.

The Respiratory System and Acid-Base Balance

- When the CO_2 is unloaded at the lungs, the preceding equation flows to the left, and causes the H^+ generated from the carbonic acid to transform back to water.
  - See Figure 7-2

How HCO_3^- Is Transformed Back into CO_2

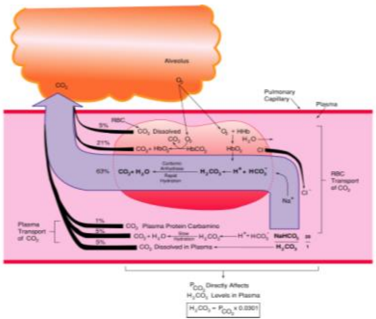

Fig. 7-2. How HCO_3^- is transformed back into CO_2 and eliminated in the alveoli.

The Respiratory System and Acid-Base Balance

- Because of the protein buffer system, the H^+ generated by the CO_2 transport system is not permitted to increase
  - Therefore, it has little or no effect on blood pH

The Respiratory System and Acid-Base Balance

- Under abnormal conditions, the respiratory system quickly responds by either increasing or decreasing the rate and depth of breathing
  - To compensate for acidosis or alkalosis, respectively

The Respiratory System and Acid-Base Balance

- For example, when the pH declines (e.g., metabolic acidosis caused by lactic acids)
  - Respiratory system responds by increasing the breathing depth and rate

The Respiratory System and Acid-Base Balance

- This action causes more CO_2 to be eliminated from the lungs and, therefore, pushes the preceding reaction to the left and reduces the H^+ concentration.
- This process works to return the acidic pH back to normal.

The Respiratory System and Acid-Base Balance

- On the other hand, when the pH rises:
  - Metabolic alkalosis caused by hypokalemia
  - Respiratory system responds by decreasing the breathing depth and rate

The Respiratory System and Acid-Base Balance

- This action causes less CO_2 to be eliminated from the lungs and, thus, moves the preceding reaction to the right and increases the H^+ concentration.
- This works to pull the alkalotic pH back to normal.

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The Respiratory System and Acid-Base Balance

- Note: When the respiratory system is impaired for any reason, a serious acid-base imbalance can develop.

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The Respiratory System and Acid-Base Balance

- For example:
  - Severe head trauma can cause a dramatic increase in the depth and rate of breathing that is completely unrelated to the CO_2 concentration.
  - When this happens, the volume of CO_2 expelled from the lungs will be greater than amount of CO_2 produced at the tissue cells.

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The Respiratory System and Acid-Base Balance

- In other words, hyperventilation is present.
- This condition causes the pH to increase and respiratory alkalosis is said to exist.

The Respiratory System and Acid-Base Balance

- In contrast:
  - The ingestion of barbiturates can cause a dramatic decrease in the depth and rate of breathing.
  - When this occurs, the volume of CO_2 eliminated from the lungs is less than the amount of CO_2 produced at the tissue cells.

The Renal System and Acid-Base Balance

- Even though the chemical buffer systems can inactivate excess acids and bases momentarily, they are unable to eliminate them from the body.

The Renal System and Acid-Base Balance

- Similarly, although the respiratory system can expel the volatile carbonic acid by eliminating CO_2, it cannot expel other acids generated by cellular metabolism.

The Renal System and Acid-Base Balance

- Only the renal system can rid the body of acids such as phosphoric acids, uric acids, lactic acids, and ketone acids
  - Also called fixed acids

The Renal System and Acid-Base Balance

- Only the renal system can regulate alkaline substances in the blood and restore chemical buffers that are used in managing H^+ levels in extracellular fluids
  - Some HCO_3^-, which helps to adjust H^+ concentrations, is lost from the body when CO_2 is expelled from the lungs.

The Renal System and Acid-Base Balance

- When the extracellular fluids become acidic, the renal system retains HCO_3^- and excretes H^+ ions into the urine
  - This causes the blood pH to increase.

The Renal System and Acid-Base Balance

- When the extracellular fluids become alkaline, the renal system retains H^+ and excretes basic substances primarily HCO_3^- into the urine
  - This causes the blood pH to decrease

THE ROLE OF THE $PCO_2/HCO_3^-/pH$ RELATIONSHIP IN ACID-BASE BALANCE

Acid-Base Balance Disturbances

- Normal bicarbonate (HCO_3^-) to carbonic acid (H_2CO_3) ratio in the blood plasma is 20:1.
- In other words, for every H_2CO_3 ion produced in blood plasma, 20 HCO_3^- ions must be formed to maintain a 20:1 ratio (normal pH).

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Acid-Base Balance Disturbances

- Or, for every H_2CO_3 ion loss in the blood plasma, 20 HCO_3^- ions must be eliminated to maintain a normal pH.
- In other words, the H_2CO_3 ion is 20 times more powerful than the HCO_3^- ion in changing the blood pH.

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Acid-Base Balance Disturbances

- Under normal conditions, the 20:1 acid-base balance in the body is automatically regulated by the:
  - Chemical buffer systems
  - Respiratory system
  - Renal system

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Acid-Base Balance Disturbances

- However, these normal acid-base regulating systems have their limits.
- The bottom line is this:
  - The body's normal acid-base watchdog systems cannot adequately respond to sudden changes in H^+ and HCO_3^- concentrations
    - Regardless of the cause

Acid-Base Balance Disturbances

- For example:
  - Hypoventilation causes the partial pressure of the alveolar carbon dioxide ($PACO_2$) to increase, which in turn causes the plasma PCO_2, HCO_3^-, and H_2CO_3 to all increase.
  - This causes HCO_3^- to H_2CO_3 ratio to decrease, and the pH to fall.
  - See Figure 7-8

Alveolar Hypoventilation

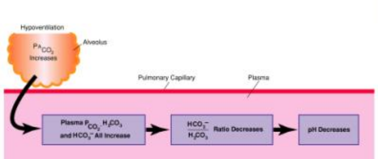

Fig. 7-8. Alveolar hypoventilation causes the $PACO_2$ and the plasma PCO_2, H_2CO_3, and HCO_3^- to increase. This action decreases the HCO_3^-/H_2CO_3 ratio, which in turn decreases the blood pH.

Acid-Base Balance Disturbances

- Or, when the $PACO_2$ decreases, as a result of alveolar hyperventilation, the plasma PCO_2, HCO_3^- and H_2CO_3 all decrease which in turn causes:
  - HCO_3^- to H_2CO_3 ratio to increase, and the pH to rise
  - See Figure 7-9

Alveolar Hyperventilation

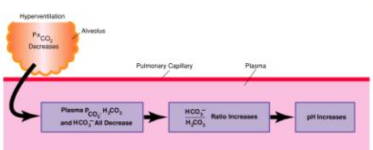

Fig. 7-9. Alveolar hyperventilation causes the $PACO_2$ and the plasma PCO_2, H_2CO_3, and HCO_3^- to decrease. This action increases the HCO_3^-/H_2CO_3 ratio, which in turn increases the blood pH.

Acid-Base Balance Disturbances

- Relationship between acute PCO_2 changes, and the resultant pH and HCO_3^- changes that occur is graphically illustrated in the $PCO_2/HCO_3^-/pH$ nomogram
  - See Figure 7-10

Nomogram of PCO_2/HCO_3^-/pH Relationship

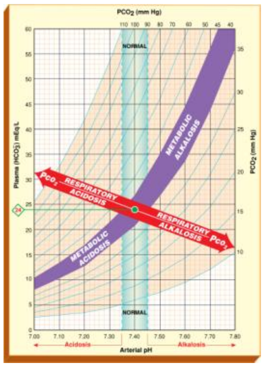

Figure 7-10 Nomogram of PCO_2/HCO_3^-/pH relationship.

Acid-Base Balance Disturbances

- PCO_2/HCO_3^-/pH nomogram is an excellent clinical tool that can be used to identify a specific acid-base disturbance
- Table 7-2 provides an overview of the common acid-base balance disturbances that can be identified on the PCO_2/ HCO_3^-/pH nomogram

Common Acid-Base Disturbance Classifications

Respiratory Acid-Base Disturbances

- Acute ventilatory failure (**respiratory acidosis**)
- Acute ventilatory failure with partial renal compensation
- Chronic ventilatory failure with complete renal compensation

- Acute alveolar hyperventilation (**respiratory alkalosis**)
- Acute alveolar hyperventilation with partial renal compensation
- Chronic alveolar hyperventilation with complete renal compensation

Table 7-2

Common Acid-Base Disturbance Classifications

Table 7-2

Metabolic Acid-Base Disturbances

- **Metabolic acidosis**
- Metabolic acidosis with partial respiratory compensation
- Metabolic acidosis with complete respiratory compensation
- Both metabolic and respiratory acidosis

- **Metabolic alkalosis**
- Metabolic alkalosis with partial respiratory compensation
- Metabolic alkalosis with complete respiratory compensation
- Both metabolic and respiratory alkalosis

Acid-Base Balance Disturbances

- The following sections will describe:
  - The common acid-base disturbances, and
  - How to identify them on the $PCO_2/HCO_3^-/pH$ nomogram.

RESPIRATORY ACID-BASE DISTURBANCES

Acute Ventilatory Failure (Respiratory Acidosis)

- During acute ventilatory failure, $PACO_2$ progressively increases
- This action simultaneously causes an increase in the blood PCO_2, H_2CO_3 and HCO_3^- levels
  - Causes blood pH to decrease or become acidic
  - See Figure 7-8

Alveolar Hypoventilation

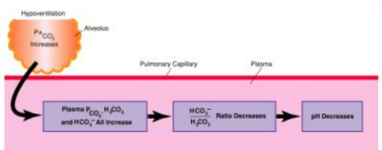

Fig. 7-8. Alveolar hypoventilation causes the PAC02 and the plasma PCO_2, H_2CO_3, and HCO_3^- to increase. This action decreases the HCO_3^-/H_2CO_3 ratio, which in turn decreases the blood pH.

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Acute Ventilatory Failure (Respiratory Acidosis)

- Resultant pH and HCO_3^- changes can be easily identified by using the left side of the red colored normal PCO_2 blood buffer bar located on the $PCO_2/HCO_3^-/pH$ nomogram
  - Titled **RESPIRATORY ACIDOSIS**
  - See Figure 7-11

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Respiratory Acidosis

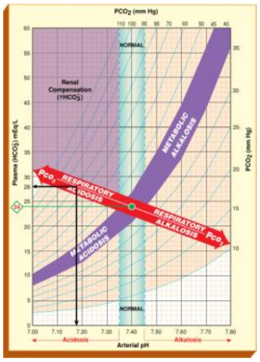

Figure 7-11 Acute ventilatory failure is confirmed when the reported PCO_2, pH and HCO_3^- values all intersect within the red colored RESPIRATORY ACIDOSIS bar. For example, when the reported PCO_2 is 80 mm Hg, at a time when the pH is 7.18 and the HCO_3^- is 28 mEq/L, acute ventilatory failure is confirmed.

Common Causes of Acute Ventilatory Failure

- Chronic obstructive pulmonary disorders
  - Pulmonary disorders such as chronic emphysema and chronic bronchitis can lead to acute ventilatory failure
- Drug overdose
  - such as narcotics or barbiturates can depress ventilation
- General anesthesia
  - Generally, anesthetics cause ventilatory failure

Table 7-3

Common Causes of Acute Ventilatory Failure

- Head trauma
  - Severe trauma to the brain can cause acute ventilatory failure
- Neurologic disorders
  - Neurologic disorders such as Guillain-Barré Syndrome and Myasthenia Gravis can lead to acute ventilatory failure.

Table 7-3

Renal Compensation

- In the patient who hypoventilates for a long period of time, the kidneys will work to correct the decreased pH by retaining HCO_3^- in the blood.
  - Chronic obstructive pulmonary disease

Renal Compensation

- The presence of renal compensation is verified when the reported PCO_2, HCO_3^-, and pH values all intersect in the purple colored area shown in the upper left-hand corner of the PCO_2 /HCO_3^-/pH nomogram
  - See Figure 7-12

Renal Compensation

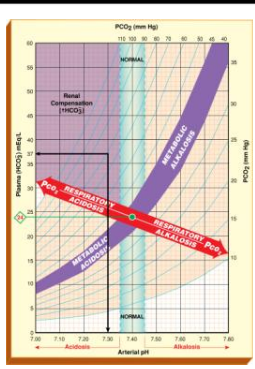

Figure 7-12 Acute ventilatory failure with partial renal compensation (also called partially compensated respiratory acidosis) is present when the reported pH and HCO_3^- are both above the normal red colored PCO_2 blood buffer bar (in the purple colored area), but the pH is still less than normal. For example, when the PCO_2 is 80 mm Hg, at a time when the pH is 7.30 and the HCO_3 is 37 mEq/L, ventilatory failure with partial renal compensation is confirmed.

Acute Ventilatory Failure with Partial Renal Compensation (Partially Compensated Respiratory Acidosis)

- Acute ventilatory failure with partial renal compensation is present when:
  - Reported pH and HCO_3^- are both above normal red colored PCO_2 blood buffer bar (in the purple colored area), but pH is still less than normal
  - See Figure 7-12

Acute Ventilatory Failure with Partial Renal Compensation

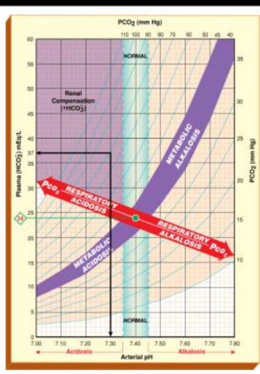

Figure 7-12 Acute ventilatory failure with partial renal compensation (also called partially compensated respiratory acidosis) is present when the reported pH and HCO_3^- are both above the normal red colored PCO_2 blood buffer bar (in the purple colored area), but the pH is still less than normal. For example, when the PCO_2 is 80 mm Hg, at a time when the pH is 7.30 and the HCO_3^- is 37 mEq/L, ventilatory failure with partial renal compensation is confirmed.

Chronic Ventilatory Failure with Complete Renal Compensation (Compensated Respiratory Acidosis)

- Present when the HCO_3^- increases enough to cause the acidic pH to move back into the normal range
  - Above 42 mEq/L
  - See Figure 7-12

Acute Ventilatory Failure with Partial Renal Compensation

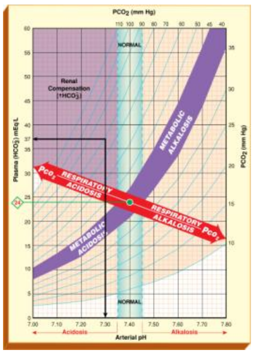

Figure 7-12 Acute ventilatory failure with partial renal compensation (also called partially compensated respiratory acidosis) is present when the reported pH and HCO_3^- are both above the normal red colored PCO_2 blood buffer bar (in the purple colored area), but the pH is still less than normal. For example, when the PCO_2 is 80 mm Hg, at a time when the pH is 7.30 and the HCO_3^- is 37 mEq/L, ventilatory failure with partial renal compensation is confirmed.

Acute Alveolar Hyperventilation (Respiratory Alkalosis)

- During acute alveolar hyperventilation, the $PACO_2$ will decrease and allow more CO_2 molecules to leave the pulmonary blood.
  – Hyperventilation due to pain and/or anxiety

Acute Alveolar Hyperventilation (Respiratory Alkalosis)

- This action simultaneously causes a decrease in the blood PCO_2, H_2CO_3, and HCO_3^- levels
  – Which, in turn, causes the blood pH to increase, or become more alkaline
  – See Figure 7-9

Alveolar Hyperventilation

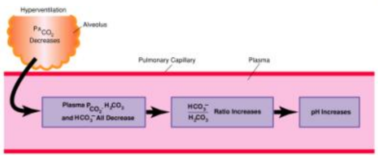

Fig. 7-9. Alveolar hyperventilation causes the $PACO_2$ and the plasma PCO_2, H_2CO_3, and HCO_3^- to decrease. This action increases the HCO_3^-/H_2CO_3 ratio, which in turn increases the blood pH.

Acute Alveolar Hyperventilation (Respiratory Alkalosis)

- Resultant pH and HCO_3^- changes caused by an acute decrease in the PCO_2 level can be identified by using the right side of the red colored normal PCO_2 blood buffer bar located on the PCO_2/HCO_3^-/pH nomogram
  - Titled **RESPIRATORY ALKALOSIS**
  - See Figure 7-13

Acute Alveolar Hyperventilation

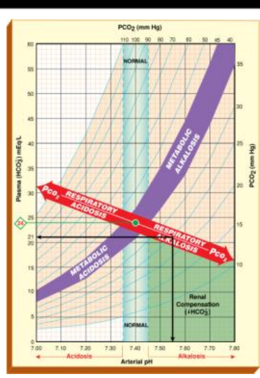

Figure 7-13. Acute alveolar hyperventilation is confirmed when the reported PCO_2, pH and HCO_3^- values all intersect within the red colored RESPIRATORY ALKALOSIS bar. For example, when the reported PCO_2 is 25 mm Hg, at a time when the pH is 7.55 and the HCO_3^- is 21 mEq/L, acute alveolar hyperventilation is confirmed.

Common Causes of Acute Ventilatory Failure

Table 7-2

- Hypoxia
  - Any cause of hypoxia (e.g., lung disorders, high altitudes, and heart disease) can cause acute alveolar hyperventilation.
- Pain, anxiety, and fever
  - Relative to the degree of pain, anxiety, and fever, hyperventilation may be seen.

Common Causes of Acute Ventilatory Failure

Table 7-2

- Brain inflammation
  - Relative to the degree of cerebral inflammation, hyperventilation may be seen.
- Stimulant drugs
  - Agents such as amphetamines can cause alveolar hyperventilation.

Renal Compensation

- In the patient who hyperventilates for a long period of time, the kidneys will work to correct the increased pH by excreting excess HCO_3^- in the urine.
  - A patient who has been overly mechanically hyperventilated for more than 24 to 48 hours

Renal Compensation

- The presence of renal compensation is verified when the reported PCO_2, HCO_3^-, and pH values all intersect in the green colored area shown in the lower right-hand corner of the PCO_2 /HCO_3^-/pH nomogram
  - See Figure 7-14

Alveolar Hyperventilation (with Partial Renal Compensation)

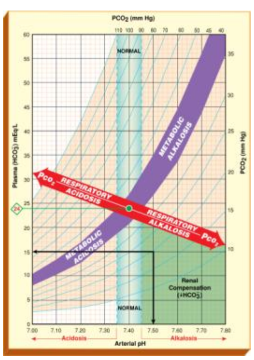

Figure 7-14 Alveolar hyperventilation with partial renal compensation (also called partially compensated respiratory alkalosis) is present when the reported pH and HCO_3^- are both below the normal red colored PCO_2 blood buffer bar (in the green colored area), but the pH is still greater than normal. For example, when the PCO_2 is 20 mm Hg, at a time when the pH is 7.50 and the HCO_3^- is 15 mEq/L, alveolar hyperventilation with partial renal compensation is confirmed.

Alveolar Hyperventilation with Partial Renal Compensation (Partially Compensated Respiratory Alkalosis)

- Alveolar hyperventilation with partial renal compensation is present when:
  - Reported pH and HCO_3^- are both below the normal red colored PCO_2 blood buffer bar (in the green colored area), but the pH is still greater than normal.
  - See Figure 7-14

Alveolar Hyperventilation with Partial Renal Compensation

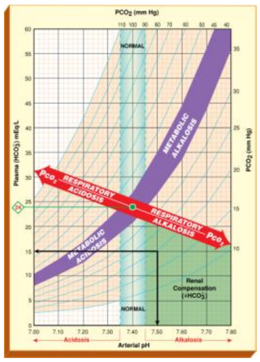

Figure 7-14. Alveolar hyperventilation with partial renal compensation (also called partially compensated respiratory alkalosis) is present when the reported pH and HCO_3^- are both below the normal red colored PCO_2 blood buffer bar (in the green colored area), but the pH is still greater than normal. For example, when the PCO_2 is 20 mm Hg, at a time when the pH is 7.50 and the HCO_3^- is 15 mEq/L, alveolar hyperventilation with partial renal compensation is confirmed.

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Chronic Alveolar Hyperventilation with Complete Renal Compensation (Compensated Respiratory Alkalosis)

- Chronic alveolar hyperventilation with complete renal compensation is present when the HCO_3^- level decreases enough to return the alkalotic pH to normal
  - Which, in this, case would be below 14 mEq/L
  - See Figure 7–14

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Chronic Alveolar Hyperventilation with Complete Renal Compensation (Compensated Respiratory Alkalosis)

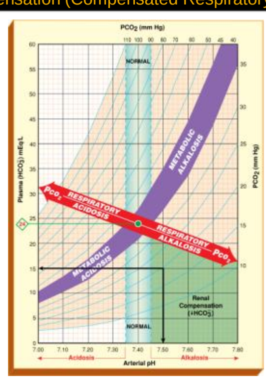

Figure 7-14 Alveolar hyperventilation with partial renal compensation (also called partially compensated respiratory alkalosis) is present when the reported pH and HCO_3^- are both below the normal red colored PCO_2 blood buffer bar (in the green colored area), but the pH is still greater than normal. For example, when the PCO_2 is 20 mm Hg, at a time when the pH is 7.50 and the HCO_3^- is 15 mEq/L, alveolar hyperventilation with partial renal compensation is confirmed.

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General Comments

- As a general rule, the kidneys do not overcompensate for an abnormal pH.
- If the patient's blood pH becomes acidic for a long period of time due to hypoventilation, the kidneys will not retain enough HCO_3^- for the pH to climb higher than 7.40.

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General Comments

- The opposite is also true:
  - Should the blood pH become alkalotic for a long period of time due to hyperventilation, the kidneys will not excrete enough HCO_3^- for the pH to fall below 7.40.

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General Comments

- However, there is one important exception to this rule:
  - In persons who chronically hypoventilate for a long period of time, it is not uncommon to find a pH greater than 7.40 (e.g., 7.43 or 7.44)
  - Patients with chronic emphysema or chronic bronchitis

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General Comments

- This is due to water and chloride ion shifts that occur between the intercellular and extracellular spaces when the renal system works to compensate for a decreased blood pH.
- This action causes an overall loss of blood chloride (hypochloremia)
  - Hypochloremia increases the blood pH

To Summarize

- The lungs play an important role in maintaining the PCO_2, HCO_3^-, and pH levels on a moment-to-moment basis.
- The kidneys, on the other hand, play an important role in balancing the HCO_3^- and pH levels during long periods of hyperventilation or hypoventilation.

METABOLIC ACID-BASE IMBALANCES

Metabolic Acidosis

- The presence of other acids, not related to an increased PCO_2 level, can also be identified on the $PCO_2/HCO_3^-/pH$ nomogram.
- Clinically, this condition is called metabolic acidosis.

Metabolic Acidosis

- Metabolic acidosis is present when the PCO_2 reading is within the normal range (35 to 45 mm Hg)—but not within the red colored normal blood buffer line when compared to the reported HCO_3^- and pH levels.

Metabolic Acidosis

- This is because the pH and HCO_3^- readings are both lower than expected for a normal PCO_2 level.

Metabolic Acidosis

- When the reported pH and HCO_3^- levels are both lower than expected for a normal PCO_2 level, the PCO_2 reading will drop into the purple colored bar—
  - Titled **METABOLIC ACIDOSIS**

Metabolic Acidosis

- In short, the pH, HCO_3^-, and PCO_2 readings will all intersect within the purple colored METABOLIC ACIDOSIS bar
  - See Figure 7-15

Metabolic Acidosis

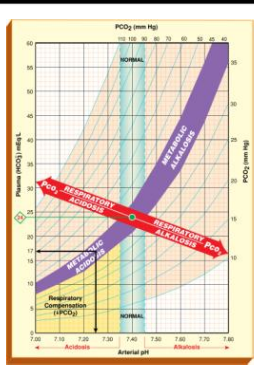

Figure 7-15. When the reported pH and HCO_3^- levels are both lower than expected for a normal PCO_2 level, the PCO_2 reading will drop into the purple colored bar titled METABOLIC ACIDOSIS. For example, when the reported PCO_2 is 40 mm Hg (normal), at a time when the pH is 7.25 and the HCO_3^- is 17 mEq/L, metabolic acidosis is confirmed.

Common Causes of Metabolic Acidosis

- Lactic acidosis
  - Fixed acids
- Ketoacidosis
  - Fixed acids

Table 7-4

Common Causes of Metabolic Acidosis

- Salicylate intoxication
  - Aspirin overdose
  - Fixed acids
- Renal failure
- Uncontrolled diarrhea

Table 7-4

Anion Gap

- To determine if a patient's metabolic acidosis is caused by either:
  1. The accumulation of fixed acids (e.g., lactic acids, keto acids, or salicylate intoxication), or
  2. By an excessive loss of HCO_3^-

Anion Gap

- According to the law of electroneutrality:
  - The total number of plasma positively charged ions (cations) must equal the total number of plasma negatively charged ions (anions) in the body fluids.
- To determine the anion gap, the most commonly measured cations are sodium (Na^+) ions.

Anion Gap

- Most commonly measured anions are the chloride (Cl^-) ions and bicarbonate (HCO_3^-) ions
- The normal plasma concentration of these cations and anions are as follows:

Na^+:	140 mEq/L
Cl^-:	105 mEq/L
HCO_3^-:	24 mEq/L

Anion Gap

- Mathematically, the anion gap is the calculated difference between the Na^+ ions and the sum of the HCO_3^- and Cl^- ions:

$$\begin{aligned} \text{Anion gap} &= [Na^+] - ([Cl^-] + [HCO_3^-]) \\ &= 140 - 105 + 24 \\ &= 140 - 129 \\ &= 11 \text{ mEq/L} \end{aligned}$$

Anion Gap

- The normal anion gap range (or the range of the unmeasured ions) is 9 to 14 mEq/L.
- An anion gap greater than 14 mEq/L represents metabolic acidosis.

Anion Gap

- An elevated anion gap is most commonly caused by the accumulation of fixed acids
  - Lactic acids
  - Keto acids
  - Salicylate intoxication

Anion Gap

- This is because the H^+ ions that are generated by the fixed acids chemically react with—and are buffered by—the plasma HCO_3^-
- This action causes:
  1. The HCO_3^- concentration to decrease, and
  2. The anion gap to increase

Anion Gap

- Clinically, when the patient presents with both metabolic acidosis and an increased anion gap, the respiratory care practitioner must investigate further to determine the source of the fixed acids.
  - This needs to be done in order to appropriately treat the patient

Anion Gap

- For example, a metabolic acidosis caused:
  1. By lactic acids justifies the need for oxygen therapy—to reverse the accumulation of the lactic acids, or
  2. By ketone acids justifies the need for insulin—to reverse the accumulation of the ketone acids.

Anion Gap

- Interestingly, metabolic acidosis caused by an excessive loss of HCO_3^- does not cause the anion gap to increase
  - Namely, renal disease or severe diarrhea

Anion Gap

- This is because as the HCO_3^- concentration decreases, the Cl^- concentration routinely increases to maintain electroneutrality.
- In other words, for each HCO_3^- that is lost, a Cl^- anion takes its place:
  - Namely, law of electroneutrality

Anion Gap

- This action maintains a normal anion gap
- Metabolic acidosis caused by a decreased HCO_3^- is often called hyperchloremic metabolic acidosis

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To Summarize

- When metabolic acidosis is accompanied by an increased anion gap, the most likely cause of the acidosis is fixed acids
  - Lactic acids
  - Ketoacids
  - Salicylate intoxication

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To Summarize

- Or, when a metabolic acidosis is seen with a normal anion gap, the most likely cause of the acidosis is an excessive lose of HCO_3^-
  - Caused by renal disease or severe diarrhea

Metabolic Acidosis with Respiratory Compensation

- The immediate compensatory response to metabolic acidosis is an increased ventilatory rate.
  - This action causes the $PaCO_2$ to decline

Metabolic Acidosis with Respiratory Compensation

- As the PCO_2 decreases, the H^+ concentration decreases
  - This action works to offset the metabolic acidosis
  - See Figure 7-9

Alveolar Hyperventilation

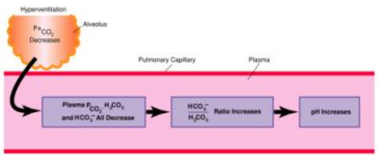

Fig. 7-9. Alveolar hyperventilation causes the $PACO_2$ and the plasma PCO_2, H_2CO_3, and HCO_3^- to decrease. This action increases the HCO_3^-/H_2CO_3 ratio, which in turn increases the blood pH.

Metabolic Acidosis with Partial Respiratory Compensation

- When pH, HCO_3^-, and PCO_2 all intersect in the yellow colored area of the $PCO_2/HCO_3^-/pH$ nomogram, metabolic acidosis with partial respiratory compensation is present

Metabolic Acidosis with Partial Respiratory Compensation

- In other words, the $PaCO_2$ has decreased below the normal range, but the pH is still below normal
  - See Figure 7-16

Metabolic Acidosis with Partial Respiratory Compensation

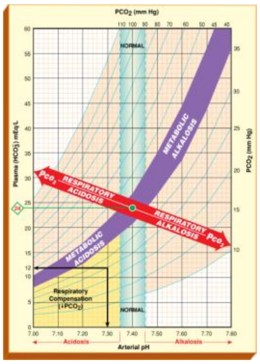

Figure 7-16 When the pH, HCO_3^-, and PCO_2 all intersect in the yellow colored area of the PCO_2/HCO_3^-/pH nomogram, metabolic acidosis with partial respiratory compensation is present. For example, when the PCO_2 is 25 mm Hg, at a time when the pH is 7.30 and the HCO_3^- is 12 mEq/L, metabolic acidosis with partial respiratory compensation is confirmed.

Metabolic Acidosis with Complete Respiratory Compensation

- Metabolic acidosis with complete respiratory compensation is present when the $PaCO_2$ decreases enough to move the acidic pH back to the normal range
  - Which, in this case, would be below 20 mm Hg
  - See Figure 7-16

Both Metabolic and Respiratory Acidosis

- When the pH, HCO_3^-, and PCO_2 readings all intersect in the orange colored area of the PCO_2/HCO_3^-/pH nomogram:
  - Both metabolic and respiratory acidosis are present
  - See Figure 7-17

Both Metabolic and Respiratory Acidosis

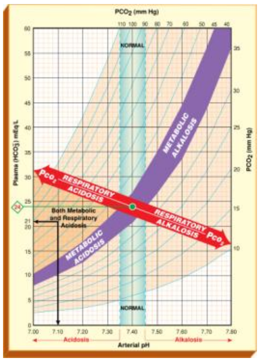

Figure 7-17 When the pH, HCO_3^-, and PCO_2 readings all intersect in the orange colored area of the PCO_2/HCO_3^-/pH nomogram, both metabolic and respiratory acidosis are present. For example, if the reported PCO_2 is 70 mm Hg, at a time when the pH is 7.10 and the HCO_3^- is 21 mEq/L, both metabolic and respiratory acidosis are present.

Both Metabolic and Respiratory Acidosis

- Both metabolic and respiratory acidosis are commonly seen in patients with acute ventilatory failure
  - Causes blood PCO_2 to increase (respiratory acidosis), and
  - PO_2 to decrease (metabolic acidosis—caused by lactic acids)

Metabolic Alkalosis

- Presence of other bases, not related to a decreased PCO_2 level or renal activity, can also be identified on the PCO_2/HCO_3^-/pH nomogram.
- Clinically, this condition is called metabolic alkalosis

Metabolic Alkalosis

- Metabolic alkalosis is present when the PCO_2 reading is within the normal range (35 to 45 mm Hg)—but not within the red normal blood buffer line when compared to the reported pH and HCO_3^- levels.
- This is because the pH and HCO_3^- readings are both higher than expected for a normal PCO_2 level.

Metabolic Alkalosis

- When reported pH and HCO_3^- levels are both higher than expected for a normal PCO_2 level, PCO_2 reading will move up into the purple colored bar titled METABOLIC ALKALOSIS
  - pH, HCO_3^-, and PCO_2 readings will all intersect within the purple colored bar.
    - See Figure 7-18

Metabolic Alkalosis

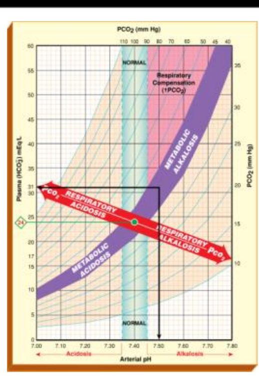

Figure 7-18. When the reported pH and HCO_3^- levels are both higher than expected for a normal PCO_2 level, the PCO_2 reading will move up into the purple colored bar titled METABOLIC ALKALOSIS. For example, when the reported PCO_2 is 40 mm Hg (normal), at a time when the pH is 7.50 and the HCO_3^- is 31 mEq/L, metabolic alkalosis is confirmed.

Common Causes of Metabolic Alkalosis

- Hypokalemia
- Hypochloremia
- Gastric suctioning or vomiting
- Excessive administration of corticosteroids
- Excessive administration of sodium bicarbonate
- Diuretic therapy
- Hypovolemia

Table 7-5

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Metabolic Alkalosis with Respiratory Compensation

- The immediate compensatory response to metabolic alkalosis is a decreased ventilatory rate.
  - This action causes the $PaCO_2$ to rise

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Metabolic Alkalosis with Respiratory Compensation

- As the PCO_2 increases, the H^+ concentration increases
  - This action works to offset the metabolic alkalosis
  - See Figure 7-8

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Metabolic Alkalosis with Respiratory Compensation

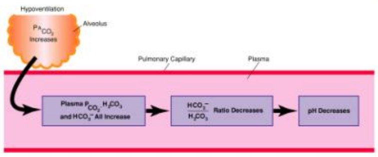

Fig. 7-8. Alveolar hypoventilation causes the $PACO_2$ and the plasma PCO_2, H_2CO_3, and HCO_3^- to increase. This action decreases the HCO_3^-/H_2CO_3 ratio, which in turn decreases the blood pH.

Metabolic Alkalosis with Respiratory Compensation

- When pH, HCO_3^-, and PCO_2 all intersect in the pink colored area of the PCO_2/ HCO_3^-/pH nomogram, metabolic alkalosis with partial respiratory compensation is present.

Metabolic Alkalosis with Respiratory Compensation

- In other words, the $PaCO_2$ has increased above the normal range, but the pH is still above normal
  - See Figure 7-19

Metabolic Alkalosis with Respiratory Compensation

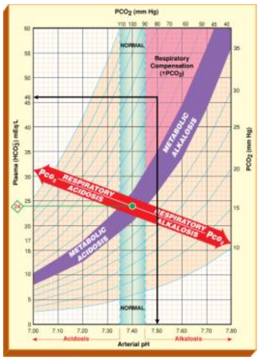

Figure 7-19. When the pH, HCO_3^-, and PCO_2 all intersect in the pink colored area of the PCO_2/HCO_3^-/pH nomogram, metabolic alkalosis with partial respiratory compensation is present. For example, when the PCO_2 is 60 mm Hg, at a time when the pH is 7.50 and the HCO_3^- is 46 mEq/L, metabolic alkalosis with partial respiratory compensation is present.

Metabolic Alkalosis with Complete Respiratory Compensation

- Metabolic alkalosis with complete respiratory compensation is present when the $PaCO_2$ increases enough to move the alkalotic pH back to the normal range
  - Which, in this case, would be above 65 to 68 mm Hg
  - See Figure 7-19

Metabolic Alkalosis with Complete Respiratory Compensation

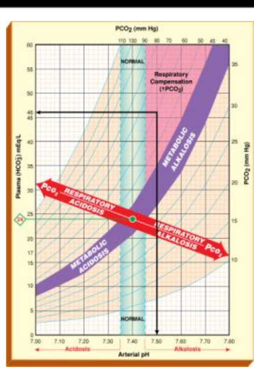

Figure 7-19 When the pH, HCO_3^-, and PCO_2 all intersect in the pink colored area of the PCO_2/HCO_3^-/pH nomogram, metabolic alkalosis with partial respiratory compensation is present. For example, when the PCO_2 is 60 mm Hg, at a time when the pH is 7.50 and the HCO_3^- is 46 mEq/L, metabolic alkalosis with partial respiratory compensation is present.

Both Metabolic and Respiratory Alkalosis

- When the pH, HCO_3^-, and PCO_2 readings all intersect in the blue colored area of the $PCO_2/HCO_3^-/pH$ nomogram,
  - Both metabolic and respiratory alkalosis are present
  - See Figure 7-20

Both Metabolic and Respiratory Alkalosis

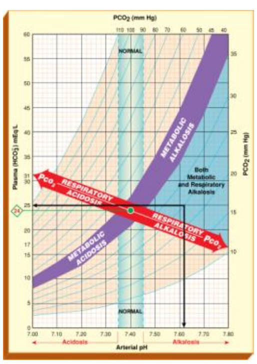

Figure 7-20. When the pH, HCO_3^-, and PCO_2 readings all intersect in the blue colored area of the $PCO_2/HCO_3^-/pH$ nomogram, both metabolic and respiratory alkalosis are present. For example, if the reported PCO_2 is 25 mm Hg, at a time when pH is 7.62 and the HCO_3^- is 25 mEq/L, both metabolic and respiratory alkalosis are present.

Base Excess/Deficit

- The $PCO_2/HCO_3^-/pH$ nomogram also serves as an excellent tool to calculate the patient's total base excess/deficit.
- By knowing the base excess/deficit, non-respiratory acid-base imbalances can be quantified.

Base Excess/Deficit

- The base excess/deficit is reported in milliequivalents per liter (mEq/L) of base above or below the normal buffer line of the $PCO_2/HCO_3^-/pH$ nomogram

Base Excess/Deficit

- For example:
- If the pH is 7.25, and the HCO_3^- is 17 mEq/L, at a time when the $PaCO_2$ is 40 mm Hg, the $PCO_2/HCO_3^-/pH$ nomogram will confirm the presence of:
  - Metabolic acidosis, and
  - A base excess of -7 mEq/L
    - More properly called a base deficit of 7 mEq/L
  - See Figure 7-15

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Metabolic Acidosis

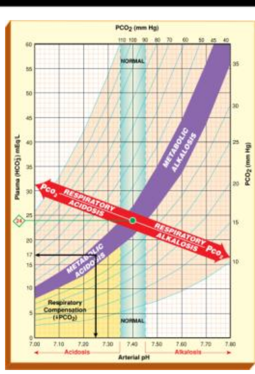

Figure 7-15 When the reported pH and HCO_3^- levels are both lower than expected for a normal PCO_2 level, the PCO_2 reading will drop into the purple colored bar titled METABOLIC ACIDOSIS. For example, when the reported PCO_2 is 40 mm Hg (normal), at a time when the pH is 7.25 and the HCO_3^- is 17 mEq/L, metabolic acidosis is confirmed.

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Base Excess/Deficit

- Metabolic acidosis may be treated by the careful intravenous infusion of sodium bicarbonate ($NaHCO_3$)

Base Excess/Deficit

- In contrast:
- If the pH is 7.50, and the HCO_3^- is 31 mEq/L, at a time when the $PaCO_2$ is 40 mm Hg, the $PCO_2/HCO_3^-/pH$ nomogram will verify the presence of:
  - Metabolic alkalosis, and
  - A base excess of 7 mEq/L
  - See Figure 7-18

Metabolic Alkalosis

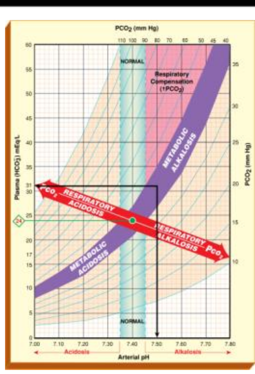

Figure 7-18 When the reported pH and HCO_3^- levels are higher lower than expected for a normal PCO_2 level, the PCO_2 reading will move up into the purple colored bar titled METABOLIC ALKALOSIS. For example, when the reported PCO_2 is 40 mm Hg (normal), at a time when the pH is 7.50 and the HCO_3^- is 31 mEq/L, metabolic alkalosis is confirmed.

Base Excess/Deficit

- Metabolic alkalosis is treated by:
  - Correcting underlying electrolyte problem
    - Namely, hypokalemia or hypochloremia
  - Administering ammonium chloride (NH_4Cl)

Example of Clinical Use of PCO_2/HCO_3^-/pH Nomogram

- It has been shown that the PCO_2/ HCO_3^-/pH nomogram is an excellent clinical tool to confirm the presence of:
  - Respiratory acid-base imbalances,
  - Metabolic acid-base imbalances, or
  - A combination of a respiratory and metabolic acid-base imbalances

Example of Clinical Use of PCO_2/HCO_3^-/pH Nomogram

- The clinical application cases at the end of this chapter further demonstrate the clinical usefulness of the PCO_2/HCO_3^-/pH nomogram

Clinical Application 1 Discussion

- How did this case illustrate …
  - How clinical signs and symptoms can sometimes be very misleading.
  - How the $PCO_2/HCO_3/pH$ nomogram can be used to determine the cause of certain findings of arterial blood gas analysis.

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Clinical Application 2 Discussion

- How did this case illustrate …
  - $PCO_2/HCO_3/pH$ nomogram can be used to confirm both a respiratory and metabolic acidosis.
  - $PCO_2/HCO_3/pH$ nomogram can be used to prevent the unnecessary administration of sodium bicarbonate during an emergency situation.

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