6 Blood Gas Analysis

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Blood gas analysis is one of the major tools in assessing the respiratory status of the newborn. To adequately use this information, one must have a basic understanding of gas transportation and acid-base physiology. These topics are addressed in this chapter to provide a basis for applying these principles to the interpretation of neonatal blood gases. Common terminology is defined in Table 6-1.

Transport of Oxygen and Carbon Dioxide

Oxygen

Oxygen is used in aerobic reactions throughout the human body and is supplied to the tissues through the efforts of the respiratory and cardiovascular systems. The lungs are responsible for bringing an adequate supply of oxygen to the blood. Control of this process occurs mainly in response to the effect of carbon dioxide (CO_2) levels on receptors in the large arteries and the brain. At moderate to severe levels of hypoxemia, peripheral chemoreceptors take the dominant role in increasing ventilation, resulting in increased oxygen intake and lower than normal partial pressure of carbon dioxide in arterial blood ($PaCO_2$).[1]

The cardiovascular system regulates the oxygen supply by altering cardiac output in response to the metabolic rate of peripheral tissues. Distribution of oxygen to specific tissues is determined by local metabolic activity. Oxygen transport is affected by:[2]

- partial pressure of oxygen in inspired air
- alveolar ventilation
- ventilation-to-perfusion matching
- arterial pH and temperature
- cardiac output
- blood volume
- hemoglobin
- hemoglobin's affinity for oxygen

Oxygen transport to the tissues can be divided into a three-phase process, involving oxygen diffusion from the alveoli to the pulmonary capillaries (external respiration) (phase 1), gas transport in the bloodstream (phase 2), and diffusion of oxygen from the capillaries to the cells (internal respiration) (phase 3). The first two phases are discussed below.

Oxygen diffuses from the alveoli to the pulmonary capillaries. Oxygen enters the lung during inspiration and diffuses across the alveolar-capillary membrane, depending on the concentration gradient of oxygen in the alveolus and the capillary (Figure 6-1). Factors that interfere with oxygenation at this point include a decrease in minute ventilation, ventilation-perfusion mismatch, and alterations in the alveolar-capillary membrane.[1]

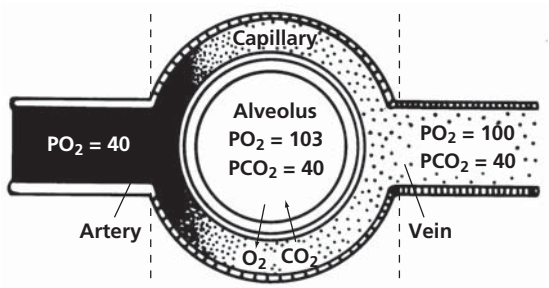
Once in the blood, oxygen must be transported to the tissues. A small amount of oxygen (about 2–5 percent) is dissolved in the plasma; 95–98 percent is bound to hemoglobin. The total volume of oxygen carried in the blood is termed the *arterial oxygen content* and reflects both the oxygen combined with hemoglobin and the amount dissolved in the plasma.

The smaller, dissolved portion of oxygen is measured as the partial pressure of oxygen (PaO_2). *Partial pressure* refers to the force the gas exerts in the blood. Through simple diffusion, gases move from an area of higher pressure to an area of lower pressure. PaO_2 is the most

TABLE 6-1
Terminology Associated with Blood Gas Analysis

Term	Definition
Acid	Donator of H^+ ions
Base	Acceptor of H^+ ions
Buffer	Weak acid and strong base pair that accept or donate hydrogen ions to maintain a balanced pH
pH	Negative logarithm of hydrogen ion
$\neq H^+$	pH more acid
Ø H^+	pH more alkaline
Acidemia	Blood pH below 7.35
Alkalemia	Blood pH above 7.45
Acidosis	Process causing acidemia
Alkalosis	Process causing alkalemia

FIGURE 6-1
Oxygen diffusion across the alveolar-capillary membrane.



From: Cherniack RM. 1972. *Respiration in Health and Disease,* 2nd ed. Philadelphia: Saunders. Reprinted by permission.

important factor in determining the amount of oxygen bound to hemoglobin. As PaO_2 increases, more oxygen diffuses into the red blood cells, where it combines with hemoglobin to form oxyhemoglobin.

Each hemoglobin molecule contains four atoms of iron and therefore can combine with four molecules of oxygen. When fully combined with oxygen, 1 g of hemoglobin carries 1.34 mL of oxygen.[1] The combination of oxygen and hemoglobin is expressed as *oxygen saturation:* a measure of the hemoglobin sites filled divided by the sites available (Figure 6-2).

Oxygen-hemoglobin saturation is plotted on an S-shaped curve known as the oxyhemoglobin dissociation curve (see Figure 4-10); this curve is based on adult hemoglobin at normal temperature and blood pH. Normal hemoglobin is 60 percent saturated at a PaO_2 of 30 mmHg and 90 percent saturated at a PaO_2 of 60 mmHg. At a PaO_2 of 90 mmHg, 95 percent of hemoglobin is saturated with oxygen.[3]

At the low PaO_2 values seen on the steep slope of the curve in Figure 4-10, a small increase in PaO_2 results in a large increase in oxygen saturation. Conversely, on the flat upper portion of the curve, a large increase in PaO_2 results in only a small increase in saturation. Hemoglobin cannot be more than 100 percent saturated, but PaO_2 can exceed 100 mmHg. At a PaO_2 of >100 mmHg, O_2 saturation cannot reflect PaO_2. For this reason, PaO_2 is a more sensitive indicator of high oxygen levels in the blood than is the measurement of saturation.[4]

Several factors change the affinity of hemoglobin for oxygen, shifting the curve to the left or to the right (see Figure 4-10). Alkalosis, hypocarbia, hypothermia, decreased amounts of 2,3-diphosphoglycerate (2,3-DPG), and the presence of fetal hemoglobin all shift the curve to the left.[1] An organic phosphate, 2,3-DPG is produced as a by-product of red cell metabolism. It binds with hemoglobin and decreases its oxygen affinity.

With a shift to the left, there is an increased affinity between oxygen and hemoglobin; therefore, hemoglobin more easily picks up oxygen and doesn't release it until the PaO_2 level falls. This can impede oxygen release to the tissues, but enhances uptake of oxygen in the lungs.[2]

Acidosis, hypercapnia, hyperthermia, increased 2,3-DPG, and the presence of mature, or adult, hemoglobin move the curve to the right.[1] A shift to the right causes oxygen to bind less tightly to hemoglobin and to release from hemoglobin at higher levels of PaO_2, thereby enhancing oxygen unloading at the tissue level.[2]

Tip: An easy way to remember how shifts in the curve affect oxygen delivery is to think of it this way: left on the hemoglobin, right into the tissues.

Carbon Dioxide

Body cells produce CO_2 as a by-product of metabolism. Carbon dioxide diffuses from the cells down a concentration gradient, from areas of high partial pressure of CO_2 to areas of low partial pressure of CO_2. A small amount (8 percent) travels dissolved in the plasma; another small portion (2 percent) is transported in the plasma bound to proteins, forming carbamino compounds.[1] The remainder is transported within the red blood cells.

In red blood cells, about 10 percent of the CO_2 forms carbamino compounds by combining with amino acids contained in the globin portion of the hemoglobin. The remaining 80 percent is acted upon by carbonic anhydrase, which combines carbon dioxide and water to form carbonic acid (H_2CO_3) and then undergoes hydrolysis and forms bicarbonate (HCO_3^-) and hydrogen ions

FIGURE 6-2
Oxygen saturation.

Saturation is equal to the percentage of hemoglobin that is carrying oxygen. Hemoglobin can be carrying either four molecules of oxygen (oxygenated) or none (deoxygenated).

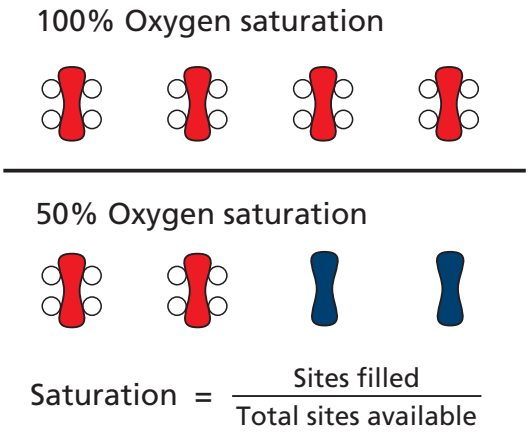
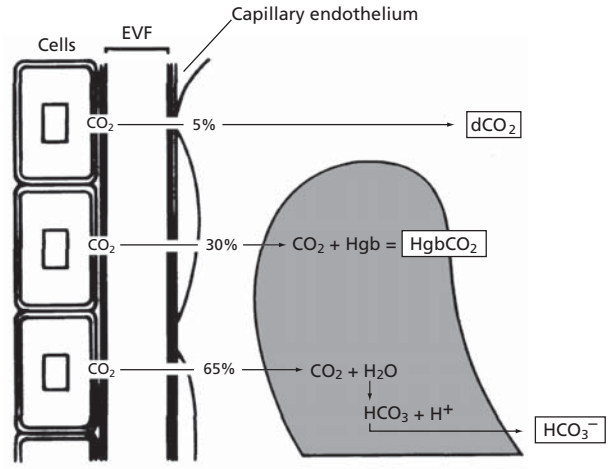


FIGURE 6-3
Carbon dioxide transport.

A schematic representation of the three major mechanisms for carbon dioxide transport in blood. dCO_2 = the carbon dioxide molecules dissolved in plasma; this is the carbon dioxide that determines the partial pressure. $HbCO_2$ = carbon dioxide chemically combined to amino acid components of hemoglobin molecules; usually referred to as carbamino-CO_2. HCO_3^- = intra-red blood cell carbonic anhydrase mechanism produces bicarbonate ions.



Key: EVF = extracellular volume fraction; Hgb = hemoglobin.

From: Shapiro BA, Peruzzi WT, and Kozelowski-Templin R. 1994. Respiratory acid-base balance. In *Clinical Application of Blood Gases.* Philadelphia: Mosby, 26. Reprinted by permission.

(H^+). The hydrogen ions are buffered by desaturated hemoglobin, and HCO_3^- is transported out of the erythrocytes into the plasma (Figure 6-3).[1] As oxygen is unloaded from hemoglobin along the tissue capillaries, more CO_2 can be transported because of the enhanced ability of deoxygenated hemoglobin to form carbamino compounds.[1]

Acid-Base Homeostasis

Normal function of the body's cells depends on maintaining a biochemical balance within a narrow range of free H^+ concentration. Free H^+ is constantly released in the body as waste products from the metabolism of proteins and fats. The measurement of free H^+ present in the body in very low concentrations is expressed as *pH,* which is the negative logarithm of the H^+ concentration—that is, the more H^+ present in a solution, the lower the pH or the more acidic the solution. Conversely, the fewer H^+ present, the higher the pH or the more alkaline the solution. A pH of 7 is neutral, that is, neither alkaline nor acidic. A pH range of 7.35–7.45 is normal for cellular reactions in the human body.

Most of the acids formed by metabolism come from the interaction of carbon dioxide and water, which forms H_2CO_3, as illustrated in the following equation:

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

Carbonic anhydrase, an enzyme, accelerates this reaction. Carbonic acid is referred to as a volatile acid because it is transformed back into CO_2 in the lungs and exhaled, allowing the respiratory system to control the majority of acid-base regulation. Sulfuric, phosphoric, and other organic acids are nonvolatile acids that are eliminated in the renal tubules.

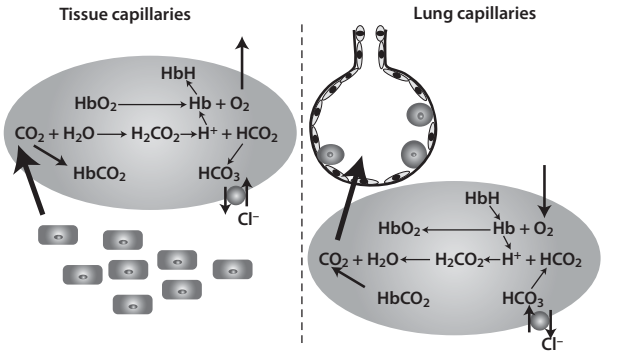
Changes in CO_2 affect pH by altering the amount of HCO_3^- in the body. Changes in pH caused by changes in CO_2 tension are therefore termed *respiratory.* Hyperventilation causes a lower partial pressure of carbon dioxide (PCO_2), lower H_2CO_3 concentration, and increased pH. Hypoventilation has the opposite effect. Remember that concentrations of CO_2, H_2CO_3, and H^+ move in the opposite direction of pH:

$$\uparrow PCO_2 \rightarrow \uparrow H_2CO_3 \rightarrow \uparrow H^+ \rightarrow \downarrow pH$$

$$\downarrow PCO_2 \rightarrow \downarrow H_2CO_3 \rightarrow \downarrow H^+ \rightarrow \uparrow pH$$

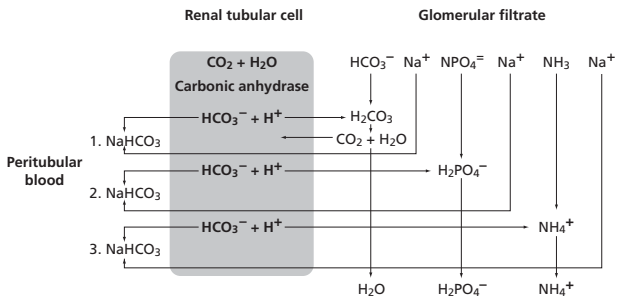
Metabolic acids are formed in the body during the metabolism of protein, anaerobic metabolism resulting in the formation of lactic acid and keto acids, which are formed when glucose is unavailable as a fuel source. The kidneys provide the most important route by which metabolic acids can be excreted and buffered.

FIGURE 6-4
The chloride shift.



Courtesy of William Diehl-Jones.

FIGURE 6-5
Mechanisms of renal bicarbonate excretion/retention.



From: Shapiro BA, Peruzzi WT, and Kozelowski-Templin R. 1994. *Clinical Application of Blood Gases,* 5th ed. Philadelphia: Mosby, 7. Reprinted by permission.

Hydrogen excretion takes place through the active exchange of sodium ions (Na^+) for H^+. The kidneys are also responsible for plasma levels of HCO_3^-, the most important buffer of H^+ (discussion follows). Therefore, pH changes that occur because of changes in bicarbonate concentrations are termed *metabolic.*

Tip: Remember the following equations:

$$\uparrow HCO_3^- \rightarrow \uparrow pH$$

$$\downarrow HCO_3^- \rightarrow \downarrow pH$$

The Henderson-Hasselbalch Equation

The concentration of H^+ resulting from the dissociation of H_2CO_3 is determined by an interrelationship between bases, buffers, and blood acids. In blood gas analysis, the Henderson-Hasselbalch equation is used to calculate HCO_3^- if pH and PCO_2 are known.[3] This equation describes the fixed relationship between H_2CO_3, HCO_3^-, and H_2CO_3 concentration. When the equation is used in the clinical situation, H_2CO_3 is replaced by the amount of dissolved CO_2 in the blood, as shown in the following equation:[3]

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

in which pK (a constant) = 6.1 and s (solubility of CO_2) = 0.0301. It is important to remember that this is a calculated bicarbonate value, not one that is measured.

Buffer Systems

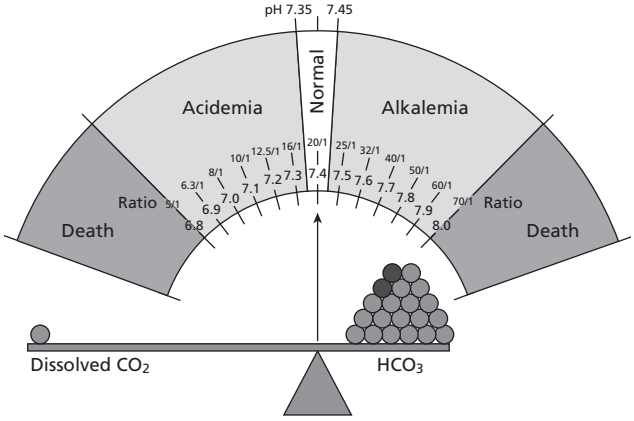
Buffer systems are a combination of a weak acid and a strong base, which work by accepting or releasing hydrogen ions to maintain acid-base balance. The body has three primary buffers: plasma proteins, hemoglobin, and bicarbonate.[5] Of these, HCO_3^- is the most important system and is regulated by the kidney. Bicarbonate ions are formed from the hydroxylation of CO_2 by water inside red blood cells, catalyzed by carbonic anhydrase. Once formed, HCO_3^- enters the plasma in exchange for chloride ions (Cl^-) through an active transport mechanism known as the chloride shift, which is depicted in Figure 6-4. In blood gas analysis, bicarbonate and base deficit/excess are used in determining the nonrespiratory portion of the acid-base equation. Some centers provide both values in blood gas results; others report either HCO_3^- levels or base excess/deficit.

Bicarbonate is expressed in milliequivalents per liter (mEq/liter). The normal range is 22–26 mEq/liter.[1] Base excess or base deficit is reported in mEq/liter, with a normal range of –4 to +4.[3] Negative values indicate a deficiency of base or an excess of acid (metabolic acidosis); positive values indicate alkalosis. Clinically, the base excess or deficit is calculated from the Siggaard-Andersen nomogram (Appendix A).

The kidney has several mechanisms for controlling excretion of H^+ and retention of HCO_3^-. These are illustrated in Figure 6-5 and include the following:[5]

- Resorption of filtered HCO_3^- (H^+ is excreted in the renal tubular cells in exchange for Na^+, which combines with HCO_3^- to form sodium bicarbonate, which enters the blood.)
- Excretion of acids (One example is phosphoric acid, which is formed from the combination of H^+ and hydrogen phosphate.)
- Formation of ammonia (NH_3) (Elevated acid levels in the body result in the formation of NH_3, which combines with H^+ to form ammonium, which is excreted in the urine.)

FIGURE 6-6
Normal 20:1 bicarbonate:carbon dioxide ratio.



From: Jacob SW, and Francone CA. 1970. *Structure and Function in Man,* 2nd ed. Philadelphia: Saunders. Reprinted by permission.

TABLE 6-2
Renal Response to Acid-Base Imbalance

Imbalance	Response
Metabolic acidosis	Phosphate and ammonia buffers are used to increase H^+ excretion.
Respiratory acidosis	H^+ excretion and HCO_3^- reabsorption are increased.
Metabolic alkalosis	HCO_3^- reclamation from the urine is decreased. H^+ excretion decreases when serum Na^+ and K^+ are normal. If hyponatremia is present, Na^+ is reabsorbed, requiring H^+ excretion and HCO_3^- retention. If hypokalemia is present, K+ is reabsorbed in place of H^+.
Respiratory alkalosis	H^+ excretion and HCO_3^- reabsorption decrease.

Adapted from: Shapiro BA, Peruzzi WT, and Kozelowski-Templin R. 1994. *Clinical Application of Blood Gases.* Philadelphia: Mosby, 8–9.

An acid-base ratio of 1:20—that is, 1 part carbonic acid to 20 parts bicarbonate—is needed to maintain a pH of 7.4.[3] It is the ratio of PCO_2 to HCO_3^- that determines the pH; therefore, abnormalities can be compensated for by adding or subtracting on one side of the scale or the other. This is demonstrated in Figure 6-6.

If buffers cannot normalize the pH, compensatory mechanisms are activated. Healthy lungs are able to compensate for acid-base imbalances within minutes by altering the respiratory rate or volume to regulate CO_2 levels. The kidneys have a slower but more sustained response, either retaining or excreting HCO_3^- in response to changes in blood pH. The kidneys are also able to excrete additional H^+ in combination with phosphate and ammonia. Renal compensatory responses are outlined in Table 6-2. In the neonate, compensatory mechanisms may be limited by respiratory disease and the inability of the immature neonatal kidney to conserve HCO_3^-.

Disorders of Acid-Base Balance

Classification and interpretation of blood gas values are based on a set of normal values, such as the ones shown in Table 6-3. Because of immaturity and the presence of fetal hemoglobin, values for the term and preterm infant differ from those of the adult. In addition, the exact values accepted as normal vary from institution to institution and in the literature.[3,6]

The terms applied to acid-base disorders can be a source of confusion. *Acidemia* and *alkalemia* refer to measurements of blood pH; *acidosis* and *alkalosis* refer to underlying pathologic processes.

As previously discussed, a blood pH <7.35 is said to be acidemic; a pH >7.45 is alkalemic. The PCO_2 and HCO_3^- levels, respectively, determine the respiratory and metabolic contributions to the acid-base equation.

During a disturbance of acid-base balance, the body can attempt to return the pH to a normal level in one of two ways:

1. **Correction** occurs when the body alters the component responsible for the abnormality. If CO_2 levels are increased, for example, the body attempts to correct the problem by increasing the excretion of it. The neonate is often unable to correct an acid-base disturbance because of the limitations of immaturity (such as diminished response of chemoreceptors and decreased lung compliance).

TABLE 6-3
Normal Arterial Blood Gas Values

Value	Normal Range
pH	7.35–7.45
$PaCO_2$	35–45 mmHg
PaO_2 term infant preterm infant	50–70 mmHg 45–65 mmHg
HCO_3^-	22–26 mEq/liter
Base excess	–2 to +2 mEq/liter
O_2 saturation	92–94%

Adapted from: Malley WJ. 2005. *Clinical Blood Gases,* 2nd ed. Philadelphia: Saunders, 4; and Durand DJ, Phillips B, and Boloker J. 2003. Blood gases: Technical aspects and interpretation. In *Assisted Ventilation of the Neonate,* 4th ed., Goldsmith JP, and Karotkin EH, eds. Philadelphia: Saunders, 290. Reprinted by permission.

TABLE 6-4
Causes of Acid-Base Imbalances in Neonates

↑$PaCO_2$

Respiratory Acidosis
Hypoventilation
- Asphyxia
- Apnea
- Upper airway obstruction
- Decreased lung tissue
  - Respiratory distress syndrome
  - Pneumothorax
  - Pulmonary interstitial emphysema

Ventilation-to-perfusion mismatching
- Meconium aspiration
- Pneumonia
- Pulmonary edema
- Transient tachypnea
- Persistent pulmonary hypertension of the newborn

Cardiac disease

Metabolic Alkalosis
Gain of bases
- Bicarbonate administration
- Acetate administration

Loss of acids
- Vomiting, gastric suctioning
- Diuretic therapy
- Hypokalemia, hypochloremia

↓pH — ↑pH

Metabolic Acidosis
Increased acid formation
- Hypoxia due to lactic acidosis
- Inborn errors of metabolism
- Hyperalimentation

Loss of bases
- Diarrhea
- Renal tubular acidosis
- Acetazolamide administration

Respiratory Alkalosis
Hyperventilation
- Iatrogenic mechanical hyperventilation
- Central nervous system response to:
  - Hypoxia
  - Maternal heroin addiction

↑$PaCO_2$

2. **Compensation** occurs when the body normalizes the pH by altering the blood gas component not responsible for the abnormality. If metabolic acidosis is present, for example, the lungs will excrete more CO_2 to normalize the pH. If respiratory acidosis is present, the kidneys will excrete more H^+ and conserve HCO_3^- in an attempt to compensate for the respiratory problem. Compensation is also limited in the neonate because of immaturity.

Respiratory Acidosis

Respiratory acidosis results from the formation of excess H_2CO_3 as a result of increased PCO_2: (↑ PCO_2 → ↑ H_2CO_3 → ↑ H^+ → ↓ pH). Blood gas findings are a low pH, high PCO_2, and normal bicarbonate levels.

Respiratory acidosis is caused by insufficient alveolar ventilation secondary to lung disease. Compensation occurs over three to four days as the kidneys increase the rates of H^+ excretion and HCO_3^- reabsorption. Compensated respiratory acidosis is characterized by a low-normal pH (7.35–7.40), with increased CO_2 and HCO_3^- levels as a result of the kidney retaining HCO_3^- to compensate for elevated CO_2 levels.

Respiratory Alkalosis

Respiratory alkalosis results from alveolar hyperventilation, which leads to a deficiency of H_2CO_3. Blood gas findings are a high pH, low PCO_2, and normal HCO_3^-.

Respiratory alkalosis is caused by hyperventilation, usually iatrogenic.[7] To compensate, the kidneys decrease H^+ secretion by retaining chloride and excreting fewer acid salts. Bicarbonate reabsorption is also decreased. The pH will be high normal (7.40–7.45), with low CO_2 and HCO_3^- levels.

Metabolic Acidosis

Metabolic acidosis results from a deficiency in the concentration of HCO_3^- in extracellular fluid. It also occurs when there is an excess of acids other than H_2CO_3. Blood gas findings are a low pH, low HCO_3^-, and normal PCO_2.

Metabolic acidosis can be caused by any systemic disease that increases acid production or retention or by problems leading to excessive base losses. Examples are hypoxia leading to lactic acid production, renal disease, or loss of bases through diarrhea.[7] If healthy, the lungs will compensate by blowing off additional CO_2 through hyperventilation. If renal disease is not significant, the kidneys will respond by increasing the excretion of acid salts and the reabsorption of HCO_3^-. The pH will be low normal (7.35–7.40), with low levels of CO_2 and HCO_3^- ions.

Metabolic Alkalosis

Metabolic alkalosis results from an excess concentration of HCO_3^- in the extracellular fluid. Blood gas findings are high pH, high HCO_3^- level, and normal PCO_2.

Metabolic alkalosis is caused by problems leading to increased loss of acids, such as severe vomiting, gastric suctioning, or increased retention or intake of bases, such as occurs with excessive administration of sodium bicarbonate. The lungs compensate by retaining CO_2 through hypoventilation. The pH will be high normal (7.40–7.45), with high levels of CO_2 and HCO_3^- ions.

Table 6-4 lists common causes of acid-base disturbances in the neonate.

Blood Gas Sampling

Blood gas analysis provides the basis for determining the adequacy of alveolar ventilation and perfusion. The accuracy of this test depends a great deal on the skill and knowledge of both the person drawing the sample and the person providing the analysis. It is therefore crucial that those performing and interpreting this

test understand appropriate techniques and potential sources of error.

Regardless of the type of sample obtained, attention should be given to the following factors:

1. **Infection control/universal precautions.** All types of blood gas sampling carry the risk of transmission of infection to the infant through the introduction of organisms into the bloodstream. In addition, the potential exposure of the clinician to the infant's blood demands the use of appropriate precautions.
2. **Bleeding disorders.** The potential for bruising and excessive bleeding should be kept in mind, particularly if an arterial puncture is being considered.
3. **Steady state.** Ideally, blood gases should measure the infant's condition in a state of equilibrium. After changing ventilator settings or disturbing the infant, a period of 20–30 minutes should be allowed for arterial blood to reach a steady state.[1] The length of time needed to reach steady state varies from infant to infant.

Intrapartum Testing

Fetal Scalp Sampling

Scalp blood pH sampling in the fetus has been shown to be a useful tool for evaluating fetal well-being in the presence of suspect fetal heart tracings.[8,9] Values are similar to umbilical cord gases obtained at delivery (Table 6-5). The accuracy of fetal scalp pH is diminished in the presence of scalp edema or caput succedaneum.[10]

A pH value of 7.25 or greater is classified as normal. Values of 7.20–7.25 are borderline and should be repeated in 30 minutes, and those below 7.20 are considered indicative of fetal acidosis.[11] Despite its clinical value, scalp sampling is not widely practiced because it is technically difficult and invasive for both the mother and the fetus.[10]

Serum lactate has been used in research settings as a method of evaluating fetal well-being. The development of hand-held microvolume devices to measure blood lactate levels has made the use of lactate levels a promising alternative to fetal scalp pH testing. A randomized controlled trial comparing fetal scalp pH to fetal lactate levels found no difference in the predictive value of the two tests, but noted that measuring serum lactate provided quicker results and fewer sampling errors than did measuring scalp pH.[12] A more recent randomized controlled trial again found there was no significant difference between lactate and pH analysis in predicting acidemia at birth.[13]

TABLE 6-5
Normal Fetal Blood Gas Values

Value	Umbilical Artery	Umbilical Vein	Fetal Scalp
pH	≥7.20	≥7.25	≥7.25
PCO_2 (mmHg)	40–50	≤40	≤50
PO_2 (mmHg)	18 ± 2	30 ± 2	≥20
Base excess (mEq/liter)	0 to –10	0 to –5	<–6

From: Martin RW, and McColgin SG. 1990. Evaluation of fetal and neonatal acid-base status. *Obstetrics and Gynecology Clinics of North America* 17(1): 225. Reprinted by permission.

Continuous Intrapartum Fetal Pulse Oximetry

The intermittent nature of fetal scalp sampling combined with the technical difficulties in obtaining accurate specimens has prompted the development of techniques to more continuously monitor fetal well-being. As an adjunct to fetal heart rate monitoring, it is now possible to continuously monitor fetal oxygenation using pulse oximetry. Studies evaluating this technology have largely focused on whether fetal oximetry can clarify the condition of the fetus in the face of a nonreassuring fetal heart rate tracing, potentially reducing the rate of unnecessary cesarean section deliveries.[14]

Cord Blood Gases

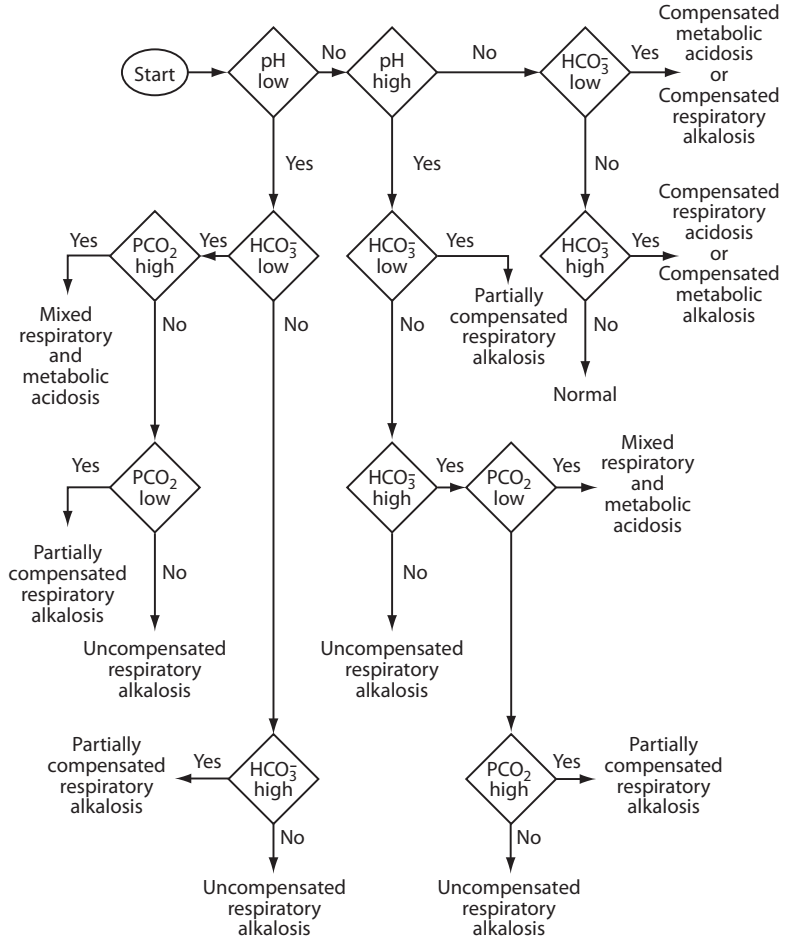
Cord blood gases provide an accurate assessment of the fetus's condition at the time of delivery, but do not predict long-term outcomes.[15] Table 6-5 lists normal umbilical cord blood gas values.

Blood from the umbilical artery represents fetal status because this is blood returning from the fetus. Umbilical venous blood provides a measure of placental status. For example, in cases of cord compression, the placenta is functioning normally. Therefore, the venous gas is normal, and the arterial gas reflects a lower pH and increased PCO_2. With decreased placental perfusion, the pH in the venous gas drops, as does the arterial pH.[9]

Arterial Sampling

Arterial blood can be obtained from the neonate either from an indwelling line or through intermittent sampling of a peripheral artery. The choice of sample site depends on the clinical situation. An indwelling arterial catheter should be placed when it is anticipated that the neonate will require frequent arterial blood sampling. Many criteria are used to determine the need for an indwelling line: These include gestational age, disease process, and the percentage of oxygen required

FIGURE 6-7
Blood gas algorithm.



From: Chatburn RL, and Carlo WA. 1988. Assessment of neonatal gas exchange. In *Neonatal Respiratory Care,* Carlo WA, and Chatburn RL, eds. St. Louis: Mosby, 56. Reprinted by permission.

by the neonate. Common sites for neonatal arterial sampling include the following:

1. **Umbilical artery.** The umbilical artery is usually readily accessible for line placement for three to four days and is often usable for up to two weeks after birth.[6] Polyvinyl chloride (PVC) or silastic catheters are available in a variety of sizes, with 3.5 and 5.0 French being the most commonly used. A Cochrane Review of umbilical catheter materials suggests that catheters constructed of silastic material may be less thrombogenic than PVC catheters.[16] The umbilical arterial catheter (UAC) should be positioned either between T6 and T10 or between L3 and L4. The distance for insertion of a high line can be estimated by measuring the distance between the infant's umbilicus and shoulder tip and adding 2 cm. The following formula, based on the infant's birth weight, can also be used:[6]

$$3 \times \textit{Weight (in kg)} + 9$$

A meta-analysis examining catheter position found a lower incidence of peripheral vascular complications associated with high line positioning. Recommendations from this review included the exclusive use of the high position for catheter placement.[17] Some caution is warranted, however, given recent studies suggesting that sampling from umbilical arterial lines, especially those in a high position, may result in disruptions in cerebral blood flow and oxygenation.[18,19] Other UAC complications include hemorrhage, ischemic organ damage, infection, and thrombus formation.[6,20,21] UAC placement is unsuccessful in 10–15 percent of infants.[6]

2. **Peripheral arterial lines** (radial, posterior tibial). These peripheral arteries can be accessed at any time beyond delivery with a small-gauge intravascular catheter. Risks for these lines include arteriospasms, tissue necrosis, thrombus formation, infection, and hemorrhage.[21]
3. **Intermittent arterial samples.** Intermittent samples can be obtained from the radial, posterior tibial, or dorsalis pedis arteries. The femoral and brachial arteries are not recommended for sampling because of poor collateral circulation, close proximity of nerves, and the risk of complications such as nerve damage or circulatory impairment.[6,22] See Figure 4-12 for a depiction of the radial site.
4. **Continuous blood gas monitoring.** Technological developments over the past 10–15 years have resulted in the development of devices that allow continuous monitoring of arterial blood gases, usually through an indwelling UAC. Studies evaluating these devices have generally been positive, demonstrating good correlation with intermittently drawn arterial gases.[23–26] Of the values measured, pH, partial pressure of oxygen (PO_2), and PCO_2. PO_2

TABLE 6-6
Compensated Acid-Based Imbalances

Primary Problem	pH	PCO_2	HCO_3^-
Respiratory acidosis	Low normal	High	High
Respiratory alkalosis	High normal	Low	Low
Metabolic acidosis	Low normal	Low	Low
Metabolic alkalosis	High normal	High	High

values were found to be the least accurate, but still within acceptable accuracy limits, in one study.[27]

See Chapter 4 for additional information on blood gas sampling techniques and considerations.

Capillary Sampling

Capillary blood can be "arterialized" by warming the skin to increase local blood flow. Samples can then be obtained from the outer aspects of the heel (see Figure 4-13) or from the side of a finger or toe. Transitional events during the first few hours of life and poor perfusion at any time diminish the accuracy of capillary gas measurements. Opinion is mixed as to the reliability of capillary blood gas values as estimators for arterial values. Some studies have found good correlation between arterial and capillary pH and PCO_2.[28–32] Others question the validity of capillary PCO_2 values and suggest caution when basing treatment decisions on capillary blood gas values.[33] Escalante-Kanashiro and Tantalean-Da-Fieno examined 75 paired arterial and capillary samples and found good correlation between pH (0.85), PCO_2 (0.86), and oxygen (0.65). Neither tissue perfusion nor temperature significantly affected correlations, but the presence of hypotension did.[34]

Other research has also demonstrated a poor correlation between PO_2 and PaO_2.[6,35] Given that finding, treatment decisions are not normally based on capillary PO_2 alone.

Errors in Blood Gas Measurement

In examining blood gases, the clinician should be aware of potential sources of error that can affect the quality of the results:[6,36,37]

- **Temperature.** Most blood gas machines report results for 37°C (98.6°F). Hypothermia or hyperthermia can alter true arterial gas values.
- **Hemoglobin.** Calculated oxygen saturations are based on adult hemoglobin, not on fetal or mixed hemoglobins.
- **Dilution.** Heparin in a gas sample lowers the PCO_2 and increases the base deficit without altering the pH.
- **Air bubbles.** Room air has a PCO_2 close to 0 and a PO_2 of 150 mmHg. Therefore, air bubbles in the sample decrease the $PaCO_2$ and increase the PaO_2 unless the PaO_2 is >150 mmHg.

Interpreting Blood Gases

The blood gas report contains many pieces of information that must be examined and interpreted. Although oxygenation and acid-base status are interrelated, it is usually easier to consider these separately. The order in which to evaluate these parameters is a matter of personal preference, but it is important to use an organized, step-by-step approach to simplify the process and ensure that nothing is overlooked.

The following steps offer a systematic way of evaluating neonatal blood gases. Figure 6-7 illustrates the first five of these steps and is a useful way of visualizing the decision-making process.

Step 1: Assess the pH. A pH >7.45 is alkalotic, and a pH <7.35 is acidotic. When pH and either PCO_2 or HCO_3^- are abnormal, the abnormal factor defines the origin of the imbalance. A normal pH should be further evaluated because compensation can normalize the pH while primary acid-base imbalances are present.

Step 2: Assess the respiratory component. A PCO_2 >45 mmHg lowers the pH. A PCO_2 <35 mmHg raises the pH.

Step 3: Assess the metabolic component. An HCO_3^- value <22 mEq/liter lowers the pH. An HCO_3^- value >26 mEq/liter raises the pH.

Tip: For primary abnormalities, remember the following:

Abnormal pH and PCO_2 = respiratory alkalosis ($PaCO_2$ <35 mmHg) or acidosis ($PaCO_2$ >45 mmHg)

Abnormal pH and HCO_3^- = metabolic acidosis (HCO_3^- <22 mEq/liter) or alkalosis (HCO_3^- >26 mEq/liter)

Mixed problems: In some cases, abnormalities in both the metabolic and the respiratory systems may be present. This is more common in acidosis than in alkalosis. If both PCO_2 and HCO_3^- are abnormal, consider the patient's history to determine which problem came first or is more severe.

Step 4: Assess the compensation status. When the pH is abnormal, with one of the acid-base components (PCO_2 or HCO_3^-) being abnormal and the other normal, the gas is said to be uncompensated.[1] When both acid-base parameters are abnormal in opposite directions, the body is beginning to compensate for the primary abnormality. When the pH reaches the normal range, the gas is compensated.

When the pH is normal and respiratory and metabolic parameters are abnormal in opposite directions (e.g., one is acidotic and one alkalotic), it may be unclear which is the primary abnormality. Because the body does not normally compensate beyond the minimum acceptable pH, the pH usually leans in the direction of the primary problem. A pH of <7.4 in a compensated gas would result from a primary acidosis with an alkalotic compensation, and a pH >7.4 would result from a primary alkalosis with an acidotic compensation.[1] Table 6-6 outlines the common findings in compensated gases.

Step 5: Complete the acid-base classification. Add the information from the blood gas analysis to the clinical assessment of the infant's condition and knowledge of the pathophysiology of the infant's disease process to determine a course of action. Remember, a blood gas result that is abnormal on paper may be quite acceptable given the infant's gestational age or disease process. For example, a pH as low as 7.25 may be considered acceptable in a preterm infant. A pH of 7.45 may be desirable if a term infant has persistent pulmonary hypertension of the newborn (PPHN).

Step 6: Evaluate the oxygenation. Three pieces of information are routinely used to determine oxygenation: PaO_2, oxygen saturation, and the presence of cyanosis. The arterial blood gas value provides information about the pulmonary component of oxygenation, specifically the PaO_2.

- **PaO_2.** Normal values for PaO_2 in the term infant are 50–70 mmHg; in the preterm infant, they are 45–65 mmHg (fetal hemoglobin results in higher saturations at lower oxygen levels).[6]

Hypoxia (inadequate tissue oxygen supply) may result from a number of factors, including heart failure, anemia, abnormal hemoglobin affinity for oxygen, and a decreased PaO_2. Hypoxemia (low PaO_2) results from lung disease or cyanotic congenital heart disease.[3] A PaO_2 value <45–50 mmHg is associated with vasoconstriction of pulmonary vasculature and vasodilation of the ductus arteriosus.[38] Low PaO_2 levels are implicated in the etiology of PPHN. Hyperoxemia (PaO_2 >90–100 mmHg) should also be avoided, especially in the preterm infant, for whom high levels of oxygen in the blood are associated with retinal injury.[38]

Note: When interpreting neonatal PaO_2 values, it may be important to identify whether the sample is preductal or postductal in origin. (See Chapter 2 for a discussion of preductal and postductal gases.)

- **Oxygen saturation.** Although oxygen saturation levels may be reported as part of an arterial blood gas result, they are more commonly obtained from an oximeter. Saturations reported as part of the blood gas result may be measured or calculated from a nomogram. Calculated saturations predict saturation based on the pH and PaO_2 and have limited clinical value.[1]

Measured oxygen saturation is usually a good indicator of reduced arterial oxygen content. Because of the shape of the oxyhemoglobin dissociation curve, saturation is not a good indicator of hyperoxemia or pulmonary deterioration.[1] PaO_2 readings of >100 mmHg occur on the flat upper portion of the curve; therefore, there is little change in oxygen saturation.

Concern regarding the incidence of retinopathy of prematurity (ROP) has prompted recommendations to maintain oxygen saturation at lower levels than those previously accepted. Tin and associates found that infants whose oxygen saturation (SpO_2) levels were maintained at between 70 and 90 percent were four times less likely to develop ROP requiring treatment than those given oxygen to maintain an SpO_2 of 88–98 percent.[39] This is substantiated by the results of a survey of 142 U.S. NICUs that demonstrated that beyond the first two weeks of life, an SpO_2 of <93 percent was associated with a significant decrease in the incidence of Stage 3 or greater ROP and the need for retinal ablation.[40] Chow and colleagues used research data to craft a practice guideline for their institution recommending that oxygen saturation levels be maintained between 85 and 93 percent. Implementation of this policy along with an education program for staff significantly decreased the rate of ROP observed in their NICU.[41]

- **Cyanosis.** Peripheral cyanosis is defined as a blue discoloration of the skin. It may be difficult to assess in dark-skinned infants. Central cyanosis is a blue discoloration of the mucous membranes and is a more reliable indicator of hypoxemia than peripheral cyanosis.

Cyanosis results from an increased amount of uncombined, or desaturated, hemoglobin. It is normally seen when the quantity of desaturated hemoglobin in the capillaries exceeds 5 g/100 mL.[1] This corresponds to a PaO_2 of about 40 mmHg. Because cyanosis depends on the quantity of desaturated hemoglobin, an anemic infant may not look cyanotic despite having a low PO_2, and an infant with polycythemia may appear cyanotic despite adequate oxygenation because of an increase in total hemoglobin.

Step 7: Formulate a plan. By following steps 1–6, the nurse can interpret blood gas values. A plan should then be formulated to accomplish the following:

- **Correct acid-base imbalances.** Correction of acid-base imbalances is achieved, where possible, through treatment of the underlying cause. Treatment suggestions for the four primary acid-base imbalances follow.
- **Respiratory acidosis.** Increase alveolar ventilation to remove CO_2 by applying nasal continuous positive airway pressure (CPAP) or mechanical ventilation. For infants already on mechanical ventilation, increase the tidal volume, rate, peak inspiratory pressure, or positive end-expiratory pressure (PEEP) to facilitate CO_2 removal (see Chapter 7). Sodium bicarbonate is not recommended for treating respiratory acidosis because it reacts with acids to form CO_2.
- **Respiratory alkalosis.** For mechanically ventilated infants, reduce the tidal volume, rate, or pressure on the ventilator.
- **Metabolic acidosis.** Where possible, treat the cause of the acidosis (e.g., correct hypovolemia, decrease the protein load in total parenteral nutrition). If the acidosis is severe, sodium bicarbonate can be administered at a dose of 2 mEq/kg or according to the following formula:

$$Base\ deficit \times Weight\ (in\ kg) \times 0.3$$

The amount of HCO_3^- calculated by this formula should theoretically correct half of the base deficit and should be administered slowly over 30–60 minutes. Fluid replacement may also be of benefit in treating metabolic acidosis by helping the infant metabolize lactic acid.[6]

Note: After fluid replacement, the infant may show a transient deterioration in acid-base status resulting from improved transport of acid from the peripheral to the central circulation.

- **Metabolic alkalosis.** Treat the cause by removing acetate from intravenous fluids, reducing diuretic doses, and replacing lost gastrointestinal secretions. Treat hyponatremia, hypokalemia, and hypochloremia.
- **Correct hypoxemia.** Hypoxemia secondary to ventilation-to-perfusion mismatching can be improved by administering supplemental oxygen. In addition, oxygenation can be improved by increasing the mean airway pressure in an infant on mechanical ventilation. Chapter 7 discusses mean airway pressure.

Case Studies

The following case studies illustrate how the steps for interpreting blood gases might be applied for various infants.

Case 1

An infant born at 31 weeks gestation is two hours old with the following physical findings: respiratory rate 94 breaths per minute, heart rate 162 beats per minute, temperature 36.5°C (97.7°F), and grunting with moderate retractions.

Capillary blood gas results are as follows:

- pH 7.30
- PCO_2 56 mmHg
- HCO_3^- 26 mEq/liter
- PO_2 40 mmHg

The steps for analysis indicate the following:

1. The pH is low, indicating acidosis.
2. The PCO_2 is high, indicating a respiratory problem.
3. The metabolic component (HCO_3^-) is normal.
4. No compensation is present (pH is not normal).
5. This is uncompensated respiratory acidosis.
6. Oxygenation is adequate.
7. Treatment should be aimed at improving alveolar ventilation. Depending on the infant's clinical status and chest x-ray findings, treatment could consist of nasal CPAP or intermittent positive pressure ventilation.

Case 2

A 26-week-gestational-age infant is receiving total parenteral nutrition (TPN) with 3.5 g/kg of protein and 15 g/kg of glucose. The infant's urine output is 7 mL/kg/hour, and the baby's weight has dropped 30 g over the past 24 hours. Capillary refill is sluggish.

Capillary blood gas results are as follows:

- pH 7.24

- PCO_2 36 mmHg
- HCO_3^- 15 mEq/liter
- PO_2 50 mmHg

The steps for analysis indicate the following:

1. The pH is low, indicating acidosis.
2. The respiratory component (PCO_2) is normal.
3. The HCO_3^- is low, indicating a metabolic problem.
4. There is no compensation (pH is not normal).
5. This is uncompensated metabolic acidosis.
6. Oxygenation is adequate.
7. Consider giving volume to compensate for hypovolemia and to help metabolize lactic acids, or reduce the amount of protein in the TPN feedings to lower the metabolic acid load.

Case 3

A 28-week-gestational-age infant is on mechanical ventilation for respiratory distress syndrome. Settings are a rate of 40 breaths per minute, tidal volume of 5 mL/kg, PEEP +4, and fractional concentration of oxygen in inspired gas (FiO_2) 0.50.

Arterial blood gas results are as follows:

- pH 7.48
- $PaCO_2$ 27 mmHg
- HCO_3^- 22 mEq/liter
- PaO_2 95 mmHg

The steps for analysis indicate the following:

1. The pH is high and shows an alkalemia.
2. The PCO_2 is low, indicating respiratory alkalosis.
3. The metabolic component (HCO_3^-) is normal.
4. There is no compensation (pH is not normal).
5. This is uncompensated respiratory alkalosis.
6. The PO_2 is too high.
7. Reduce alveolar ventilation. Assess the infant's chest expansion and spontaneous respirations to determine whether the tidal volume or the ventilator rate should be lowered. Reduce the FiO_2, ensuring that the oxygen saturation remains within the desired range.

Case 4

A three-week-old infant underwent bowel surgery three days ago. On continuous gastric suction, the infant is receiving TPN with sodium and potassium acetate.

Capillary blood gas results are as follows:

- pH 7.51
- PCO_2 43 mmHg
- HCO_3^- 34 mEq/liter
- PO_2 52 mmHg

The steps for analysis indicate the following:

1. The pH is high, showing an alkalemia.
2. The respiratory component (PCO_2) is high normal.
3. The HCO_3^- is high, leading to metabolic alkalosis.
4. There is no compensation.
5. This is uncompensated metabolic alkalosis.
6. The PO_2 is adequate.
7. Consider eliminating the acetate in the TPN in favor of chloride salts. Ensure that the serum sodium and potassium are adequate.

Case 5

An infant born at 26 weeks gestational age is now three weeks old and receiving mechanical ventilation for chronic lung disease. The infant is on full nasogastric feedings.

Capillary blood gas results are as follows:

- pH 7.37
- PCO_2 49 mmHg
- HCO_3^- 34 mEq/liter
- PO_2 52 mmHg

The steps for analysis indicate the following:

1. The pH is normal.
2. The PCO_2 is high, suggesting respiratory acidosis.
3. The HCO_3^- is high, suggesting a metabolic alkalosis.
4. The pH is normal with abnormal CO_2 and HCO_3^-; therefore, there is compensation. The pH is low normal; therefore, it is compensated acidosis. The high HCO_3^- does not fit with acidosis, but the high PCO_2 does.
5. This is compensated respiratory acidosis that fits with the clinical history of chronic lung disease.
6. Oxygen levels are satisfactory.
7. This infant's kidneys have become efficient at conserving HCO_3^- and excreting H^+, so treatment is not necessary. Keep in mind that further changes in the infant's condition (atelectasis, pneumonia, or metabolic causes of acidosis) will likely exceed the infant's ability to compensate and result in acidosis.

Case 6

A term infant, with Apgar scores of 4 at one minute and 6 at five minutes and born through thick meconium, is pale, with retractions and grunting respirations. Temperature is 35.8°C (96.4°F).

Capillary blood gas results are as follows:

- pH 7.25
- PCO_2 49 mmHg
- HCO_3^- 16 mEq/liter
- PO_2 35 mmHg

The steps for analysis indicate the following:

1. The pH is low, indicating an acidosis.

2. The PCO_2 is high, suggesting a respiratory acidosis.
3. The HCO_3^- is low, suggesting a metabolic acidosis.
4. No compensation is present.
5. This is a mixed respiratory and metabolic acidosis that is uncompensated.
6. The PO_2 is low.
7. Warm the infant slowly. Improve the alveolar ventilation, and provide supplemental oxygen. Do not administer HCO_3^- unless ventilation is improved.

Summary

Interpretation of a blood gas requires a systematic approach based on an understanding of the physiology of gas transport and acid-base balance. Such an approach permits timely and appropriate interventions aimed at providing optimal care for the compromised infant.

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Notes