Arterial Blood Gas (ABG) Analysis

ABG analysis is an indispensable test for critically ill patients or patients treated in an ICU. Interpretation of ABG analysis seems complicated; however, an understanding of the basic physiology can ease the interpretation. In this article, the basic physiology behind ABG analysis and a stepwise approach to interpreting ABG analysis will be discussed in detail.

Overview of ABG Analysis

Analysis of arterial blood gases (ABG) is an essential investigation in the management of critically ill patients as it provides important information about alveolar ventilation, oxygenation, and acid-base balance.

Measurement of ABG includes measurement of three parameters, i.e., pH, PaCO₂, and PaO₂; however, measurement of bicarbonate (HCO₃⁻) and electrolytes is almost always done simultaneously to complete the whole picture of acid-base & electrolyte balance/imbalance.

Important values

pH

- Normal blood pH: 7.36–7.44
- Acidemia: pH < 7.35
- Alkalemia: pH > 7.45

PaCO₂ & PaO₂
- Normal \(\text{PaO}_2\): 80–100 mm Hg
- Normal \(\text{PaCO}_2\): 36–44 mm Hg
- Respiratory acidosis: Acidemia with \(\text{PaCO}_2 > 44\ \text{mm Hg}\)
- Respiratory alkalosis: Alkalemia with \(\text{PaCO}_2 < 36\ \text{mm Hg}\)

\(\text{HCO}_3^-\)
- Normal \(\text{HCO}_3^-\): 20–28 mEq/L
- Metabolic acidosis: Acidemia with \(\text{HCO}_3^- < 20\ \text{mEq/L}\)
- Metabolic alkalosis: Alkalemia with \(\text{HCO}_3^- > 28\ \text{mEq/L}\)
- Normal base excess/deficit: 0 ± 2 mEq/L

**Anion Gap**
- Normal Anion Gap (AG): 12 mEq/L
- Anion Gap Metabolic Acidosis (AGMA): Metabolic acidosis with AG > 12
- Non-Anion Gap Metabolic Acidosis (NAGMA): Metabolic acidosis with normal AG

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**Basic Physiological Concepts**

\(\text{PaCO}_2\) is the best parameter that **reflects alveolar ventilation**; high (> 44 mm Hg) and low (< 36 mm Hg) \(\text{PaCO}_2\) levels suggest alveolar hypoventilation and alveolar hyperventilation respectively.

The **status of oxygenation** is affected mainly by \(\text{PaO}_2\), \(\text{FiO}_2\), and hemoglobin **content** along with its affinity and saturation with oxygen. The presence of hypoxemia (\(\text{PaO}_2 < 80\ \text{mm Hg at sea level while breathing room air}\)) does not necessarily mean the
presence of hypoxia.

Blood pH is maintained in the narrow range (7.36–7.44) by lungs, kidneys and blood buffers. In general, the blood buffer system (H₂CO₃/HCO₃⁻) acts within a fraction of seconds, the respiratory system takes about 1–15 minutes, and kidneys may take many minutes to many days to adjust H⁺ ions concentration.

PaCO₂ is mainly controlled by lungs and is a marker of respiratory acid-base disturbance. HCO₃⁻ is mainly controlled by kidneys and blood buffers, but it does not always purely indicate metabolic acid-base disturbance as it is affected by hydrolysis effect.

Plasma bicarbonate can be calculated using the Henderson-Hasselbalch equation; while standard bicarbonate is plasma bicarbonate obtained after blood has been equilibrated at 37°C with a PaCO₂ of 40 mm Hg.

**Henderson-Hasselbalch equation:**  \[ pH = 6.1 + \log_{10} \left( \frac{[\text{HCO}_3^-]}{0.03 \times \text{PaCO}_2} \right) \]

The difference between the measured bicarbonate and the calculated bicarbonate is known as base excess (if positive value) or base deficit (if negative value).

In acidemia, an excess of H⁺ ions enter intracellular space, hence, K⁺ ions move out from intracellular space into the plasma to maintain electroneutrality. Thus, acidemia is associated with hyperkalemia.

In distal renal tubular cells, K⁺ or H⁺ ions are exchanged for Na⁺ ions. In alkalemia, as H⁺ ions are retained, K⁺ ions are exchanged for Na⁺ ions, leading to hypokalemia.

**Compensation:** In response to primary acid-base disturbance, the respiratory system or kidneys attempt to maintain normal pH by the compensatory response. Compensation “moves the pH towards normal”, but compensation can never “overshoot” the normal pH.

Respiratory compensation for a primary metabolic derangement is immediate and usually improves over the course of hours, while renal compensation for a primary respiratory derangement is gradual and improves over days as it takes time for the kidneys to generate/eliminate HCO₃⁻.
Anion Gap (AG)

Calculation of anion gap is very important for metabolic acidosis. In electroneutrality:

Unmeasured anions + Cl\(^-\) + HCO\(_3\^-\) = Unmeasured cations + Na\(^+\)

Unmeasured anions are usually proteins, SO\(_4\), PO\(_4\), organic anions, etc. and unmeasured cations are K\(^+\), Ca\(^{++}\), Mg\(^{++}\), etc. Therefore:

\[
\text{Anion Gap (AG)} = \text{Na}^+ - (\text{Cl}^- + \text{HCO}_3^-) = \text{Unmeasured anions} - \text{Unmeasured cations}
\]

An elevated anion gap refers to an increase in unmeasured anions. **Normal AG: 12 mEq/L**

Respiratory Acidosis

**Key features: pH < 7.35 with PaCO\(_2\) > 44 mm Hg**

**Causes:** Basically, causes of respiratory acidosis are those that cause CO\(_2\) retention or hypoventilation.

- Upper airway disorders such as obstruction, laryngospasm, obstructive sleep apnea
- Lower airway disorders such as COPD, asthma
- Thoracic cage abnormalities restricting respiratory movements such as flail chest, kyphoscoliosis
- Neuromuscular disorders affecting ventilation such as AIDP
- CNS depression due to CNS disorders, opioids, sedatives, etc.
- Respiratory muscle fatigue following any prolonged/severe respiratory disease

Respiratory Alkalosis

**Key features: pH > 7.45 with PaCO\(_2\) < 36 mm Hg**

**Causes:** Basically, causes of respiratory alkalosis are those that cause CO\(_2\) washout or hyperventilation.

- Hyperventilation due to pain, anxiety, hysteria, CNS tumor/disorder, pulmonary embolism, etc.
- Hypoxemia due to high altitude or any other cause
- Early salicylate poisoning

Metabolic Acidosis

**Key features: pH < 7.35 with HCO\(_3\^-\) < 20 mEq/L**

Metabolic acidosis is further sub-classified on the basis of anion gap.

\[
\text{Anion Gap (AG)} = \text{Na}^+ - (\text{Cl}^- + \text{HCO}_3^-)/p>
\]

Causes of high Anion Gap Metabolic Acidosis (AGMA) (AG > 12 mEq/L):

- Methanol (formic acid) poisoning
- Uremia
- Diabetic ketoacidosis, Drugs
- Propylene glycol poisoning
- Iron poisoning, Isoniazid
- Lactic acidosis
- Ethylene glycol (→ oxalic acid) poisoning, Ethanol poisoning (Alcoholic ketoacidosis)
- Salicylate poisoning

⇒ Mnemonic: **MUDPILES**

OR

- Lactic acidosis
- Uremia
- Salicylate poisoning
- Iron poisoning, Isoniazid
- Diabetic ketoacidosis, Drugs
- Alcohol poisoning (methanol, ethanol, ethylene glycol, propylene glycol)

⇒ Mnemonic: **LUSID Alcohol**

Causes of Normal Anion Gap Metabolic Acidosis (NAGMA):

- Hyperalimentation (TPN)
- Aldosterone related (Addison disease, spironolactone, RTA type IV)
- Acetazolamide
- Renal tubular acidosis
- Diarrhea, ureteral Diversion (ileal loop), after DKA treatment
- Fluids (after volume resuscitation with low HCO₃⁻ fluids such as normal saline)

⇒ Mnemonic: **HAARD Fluids**

### Metabolic Alkalosis

**Key features: pH > 7.45 with HCO₃⁻ > 28 mEq/L**

Metabolic alkalosis is further sub-classified into saline-responsive (generally low urine Cl⁻) and saline-resistant (generally high urine Cl⁻) metabolic alkalosis. Causes of saline-responsive metabolic alkalosis:

- Gastrointestinal losses (emesis, nasogastric tube aspiration, villous adenoma, etc)
- Diuretics
- Post-hypercapnia

⇒ Mnemonic: **GDP**

Causes of saline-resistant metabolic alkalosis:

- Licorice ingestion
- Mineralocorticoid excess (hyperm Aldosteronism, Cushing’s syndrome, exogenous administration)
- Bartter’s syndrome
- Exogenous Alkali load
- Gitelman’s syndrome

⇒ Mnemonic: **LiMi BAG**
Stepwise Approach to Interpret ABG Analysis

Step 1: Is there acidemia or alkalemia?
- If pH < 7.35 → Acidemia
- If pH > 7.45 → Alkalemia

Step 2: Use PCO$_2$ to determine the primary derangement

In acidemia:
- If PCO$_2$ > 40 mm Hg → Respiratory acidosis
- If PCO$_2$ < 40 mm Hg → Metabolic acidosis

In alkalemia:
- If PCO$_2$ > 40 mm Hg → Metabolic alkalosis
- If PCO$_2$ < 40 mm Hg → Respiratory alkalosis

Step 3: Determine if compensation is adequate

For primary metabolic derangement, respiratory compensation is usually immediate and improves over the course of hours. For primary respiratory derangement, renal compensation is usually gradual and improves over days. It also depends on whether the condition is acute or chronic.
In respiratory acidosis, for every 10 mm Hg increase in PaCO₂:
- In acute condition: pH decreases by 0.08 and HCO₃⁻ increases by 1
- In chronic condition: pH decreases by 0.03 and HCO₃⁻ increases by 4

In respiratory alkalosis, for every 10 mm Hg decrease in PaCO₂:
- In acute condition: pH increases by 0.08 and HCO₃⁻ decreases by 2
- In chronic condition: pH increases by 0.03 and HCO₃⁻ decreases by 4

Step 3a: If the expected value for the level of compensation does not correlate with the measured value (pH or HCO₃⁻), then there is likely a mixed disorder present

In metabolic derangements:
- If PCO₂ is higher than expected → Concomitant respiratory acidosis
- If PCO₂ is lower than expected → Concomitant respiratory alkalosis

In respiratory derangements:
If pH is higher than expected → Concomitant metabolic alkalosis
If pH is lower than expected → Concomitant metabolic acidosis

Step 4: For all metabolic acidosis, calculate the Anion Gap

Anion gap = Na\(^+\) - (Cl\(^-\) + HCO\(_3^+\)) (Normal: 12 mEq/L)

AG should be corrected for hypoalbuminemia: For every 1 mg/dL below 4 → subtract 3 to the “normal” anion gap.

For elevated anion gap metabolic acidosis (AGMA):

Important work up for AGMA includes urine ketones, renal function tests, serum lactate, toxin screen and osmolar(OG). (See the causes.)

- OG = Measured osmolality - Calculated osmolality
- Calculated osmolality = 2(Na\(^+\)) + Glucose/18 + BUN/2.8
- If OG > 10 → suggests the possibility of ingestion as a cause of AGMA

Another important consideration is to calculate \(\Delta AG\) (change in AG) and \(\Delta HCO_3^-\) (change in bicarbonate).

\[ \Delta AG = \text{Patient’s AG} - \text{Normal AG} \]

- If \(\Delta AG = \Delta HCO_3^-\) → pure AGMA
- If \(\Delta AG > \Delta HCO_3^-\) → concomitant metabolic alkalosis
- If \(\Delta AG < \Delta HCO_3^-\) → concomitant non-anion gap metabolic acidosis or chronic respiratory acidosis

**Example 1:** \(HCO_3^- = 16, AG = 20\)
Unmeasured anions $\Delta AG = 20 - 12 = 8$ (normal AG = 12)
$\Delta HCO_3^- = 24 - 16 = 8$ (normal $HCO_3^-$ = 24)

Thus, $\Delta HCO_3^- = \Delta AG = 8 \rightarrow$ pure AGMA

**Example 2: $HCO_3^- = 10$, AG = 20**

Unmeasured anions $\Delta AG = 20 - 12 = 8$
$\Delta HCO_3^- = 24 - 10 = 14$

Thus, $\Delta HCO_3^- \neq \Delta AG$

8 mEq of change in $HCO_3^-$ is accounted for by AG acidosis; additional $(14 - 8 =) 6$ mEq of change in $HCO_3^-$ must have been caused by non-AG acidosis $\rightarrow$ combined AG and non-AG acidosis.

For normal anion gap metabolic acidosis (NAGMA):

Check Urine Anion Gap: $UNa^+ + UK^+ - UCl^-$
- If urine AG is positive, it implies $HCO_3^-$ loss by the kidneys as in renal tubular acidosis.
- If urine AG is negative, it implies $HCO_3^-$ loss from an external source as in gastrointestinal losses.

**Step 5: Review differential diagnosis**

Refer to causes of acid-base disorders described above and correlate them with the conclusion before making a final diagnosis.

**Review Questions**

The correct answers can be found below the references.

1. **Which of the following is not associated with high anion gap metabolic acidosis?**
   - A. Salicylate poisoning
   - B. Iron poisoning
   - C. Acetazolamide poisoning
   - D. Ethanol poisoning
   - E. Isoniazid poisoning

2. **Which of the following conditions is associated with saline-responsive metabolic alkalosis?**
   - A. Post-hypercapnia
   - B. Licorice ingestion
   - C. Cushing’s syndrome
   - D. Exogenous alkali administration
   - E. Gitelman’s syndrome

3. **In a patient with metabolic acidosis, anion gap is 22 mEq/L and serum $HCO_3^-$ is 16 mEq/L. What is the acid-based imbalance?**
   - A. Pure anion gap metabolic acidosis
   - B. Anion gap metabolic acidosis with concomitant non-anion gap metabolic acidosis
C. Anion gap metabolic acidosis with concomitant respiratory acidosis
D. Anion gap metabolic acidosis with concomitant metabolic alkalosis
E. Anion gap metabolic acidosis with concomitant non-anion gap metabolic acidosis and respiratory acidosis

References

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Blood Gases via nlm.nih.gov

Correct answers: 1C, 2A, 3D

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