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Arterial Blood Gas Analysis: A Biochemical Perspective on Interpretation.

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ABSTRACT

Arterial Blood Gas (ABG) analysis is a cornerstone diagnostic tool in clinical medicine, providing rapid assessment of acid-base balance, oxygenation, ventilation, and metabolic status. From a biochemical perspective, ABG interpretation integrates principles of buffer chemistry, respiratory physiology, and renal regulation to evaluate disturbances in homeostasis. Understanding the biochemical mechanisms underlying acid-base disorders enables clinicians and laboratory professionals to accurately diagnose and manage critically ill patients. This review discusses the biochemical basis of ABG parameters, acid-base physiology, systematic interpretation, common disorders, and clinical applications.

Keywords: Arterial blood gas, Acid-base balance, Bicarbonate, pH, Carbon dioxide, Base excess, Anion gap, Buffer systems, Biochemistry.

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INTRODUCTION

Maintenance of acid-base homeostasis is essential for normal cellular metabolism and enzymatic activity. The extracellular pH is tightly regulated between **7.35 and 7.45**, and even minor deviations may significantly impair physiological function. Arterial Blood Gas (ABG) analysis provides immediate information regarding respiratory function, metabolic status, and tissue oxygenation.

From a biochemical standpoint, ABG interpretation is based on the interaction between carbon dioxide (CO₂), bicarbonate (HCO₃⁻), hydrogen ions (H⁺), and physiological buffer systems. The test plays an indispensable role in intensive care, emergency medicine, pulmonary medicine, anesthesia, nephrology, and clinical biochemistry laboratories [1-4].

Biochemical Basis of Acid–Base Homeostasis

Acid-base balance is maintained through three major biochemical mechanisms:

- **Chemical buffer systems**
- **Respiratory regulation**
- **Renal regulation**

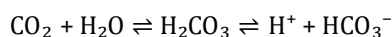
Chemical Buffer Systems

Chemical buffers provide immediate resistance to changes in pH.

Bicarbonate Buffer System

The bicarbonate buffer system is the most important extracellular buffer.

Reaction:



The reaction is catalyzed by **carbonic anhydrase** in erythrocytes.

This equilibrium forms the basis of ABG interpretation.

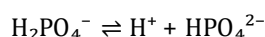
Protein Buffer System

Proteins contain amino and carboxyl groups capable of accepting or donating hydrogen ions. Major protein buffers include:

- Hemoglobin
- Plasma proteins
- Albumin

Phosphate Buffer System

The phosphate buffer functions mainly intracellularly and within renal tubules.



Respiratory Regulation

The lungs regulate blood pH by controlling arterial partial pressure of carbon dioxide (PaCO₂). Normal PaCO₂:

35–45 mmHg

Increased ventilation decreases CO₂ and raises pH.

Reduced ventilation increases CO₂ and lowers pH.

Renal Regulation

The kidneys regulate acid-base balance by:

- Reabsorbing bicarbonate
- Excreting hydrogen ions
- Producing new bicarbonate
- Generating ammonium (NH₄⁺)

Renal compensation generally requires **24–72 hours**.

Sample Collection for Arterial Blood Gas Analysis

Accurate arterial blood gas (ABG) results depend on proper sample collection, handling, and prompt analysis. Pre-analytical errors are among the most common causes of inaccurate ABG interpretation.

Site of Arterial Puncture

The preferred sites for arterial blood sampling include:

Radial artery (first choice): Easily accessible, superficial, and has collateral circulation through the ulnar artery.

Brachial artery: Used when radial artery access is not feasible; however, it has limited collateral circulation and a higher risk of complications.

Femoral artery: Preferred in emergency situations, hypotension, or cardiac arrest because it is larger and easier to palpate.

Materials Required

- Sterile pre-heparinized arterial blood gas syringe (1–3 mL)
- 22–25-gauge needle
- Alcohol or chlorhexidine antiseptic solution
- Sterile gloves
- Gauze pads and adhesive dressing
- Ice slurry (if analysis will be delayed)

Procedure

- Verify patient identity and explain the procedure.
- Perform the Allen test before radial artery puncture to assess collateral circulation.
- Clean the puncture site using aseptic technique.
- Insert the needle at a 30–45° angle toward the arterial pulse.
- Allow arterial pressure to fill the syringe without pulling the plunger.
- Remove the needle and immediately apply firm pressure to the puncture site for at least 5–10 minutes (longer in patients receiving anticoagulant therapy).
- Expel all visible air bubbles from the syringe.
- Mix the sample gently by rolling the syringe to distribute heparin evenly.
- Label the specimen with patient identification, date and time of collection, oxygen therapy status, fraction of inspired oxygen (FiO₂), and collector identification.
- Analyze the sample immediately, preferably within 15 minutes. If immediate analysis is not possible, store the specimen on ice and analyze within 30–60 minutes according to institutional protocols.

Precautions

- Avoid venous contamination.
- Minimize exposure to air, which may alter PaO₂ and PaCO₂ values.
- Prevent clot formation by using an appropriate amount of heparin and thorough mixing.
- Ensure prompt transport to the laboratory.
- Record the patient's body temperature and oxygen supplementation, as these factors influence ABG interpretation.

Allen Test

Definition

The Allen test is a simple bedside assessment performed before radial artery puncture to evaluate the adequacy of collateral blood flow through the ulnar artery. It helps determine whether the hand is likely to remain adequately perfused if the radial artery becomes temporarily or permanently occluded.

Principle

The hand receives blood from both the radial and ulnar arteries, which are connected by the superficial and deep palmar arches. A patent ulnar artery can maintain adequate hand perfusion if radial artery flow is interrupted.

Procedure

- Ask the patient to elevate the hand and make a tight fist for approximately 30 seconds.
- Compress both the radial and ulnar arteries simultaneously using firm digital pressure.
- Ask the patient to relax and open the hand. The palm should appear pale due to temporary interruption of blood flow.
- Release pressure over the **ulnar artery** while maintaining compression of the radial artery.
- Observe the return of normal color to the palm and fingers.

Interpretation

Result	Observation	Interpretation
Positive (Normal) Allen Test	Normal color returns within 5–10 seconds	Adequate collateral circulation; radial artery puncture can be performed safely.
Equivocal	Color returns within 10–15 seconds	Collateral circulation may be reduced; interpret with caution and consider alternative assessment if indicated.
Negative (Abnormal) Allen Test	Color does not return within 15 seconds	Inadequate collateral circulation; avoid radial artery puncture and consider another arterial site.

Limitations

The Allen test is easy to perform but has limited sensitivity and specificity and is subject to observer variability. In selected patients, particularly those undergoing repeated arterial cannulation or invasive procedures, objective methods such as Doppler ultrasonography or pulse oximetry-assisted modified Allen testing may provide a more reliable assessment of collateral circulation.

Possible Complications of Arterial Puncture

Although arterial puncture is generally safe, complications may occur, including:

- Local pain and discomfort
- Hematoma

- Persistent bleeding
- Arterial vasospasm
- Thrombosis
- Infection
- Nerve injury
- Distal ischemia (rare)
- Pseudoaneurysm (rare)

Proper technique, performance of the Allen test before radial artery puncture, and adequate post-procedure compression significantly reduce the risk of complications.

Principle of Arterial Blood Gas Analysis

ABG analysis measures:

- Blood pH
- PaCO_2
- PaO_2
- HCO_3^-
- Oxygen saturation (SaO_2)
- Base excess (BE)

Modern analyzers utilize:

- Potentiometry for pH
- Severinghaus electrode for CO_2
- Clark electrode for oxygen

Bicarbonate concentration is calculated using the **Henderson-Hasselbalch equation**.

Biochemical Parameters of ABG

Parameter	Normal Range	Biochemical Significance
pH	7.35–7.45	Hydrogen ion concentration
PaCO_2	35–45 mmHg	Respiratory component
HCO_3^-	22–26 mmol/L	Metabolic component
Base Excess	–2 to +2 mmol/L	Metabolic deviation
PaO_2	80–100 mmHg	Oxygenation status
SaO_2	95–100%	Hemoglobin oxygen saturation
Lactate	<2 mmol/L	Tissue perfusion marker

Henderson-Hasselbalch Equation

The biochemical relationship between pH, bicarbonate, and carbon dioxide is expressed as:

$$\text{pH} = 6.1 + \log [\text{HCO}_3^- / (0.03 \times \text{PaCO}_2)]$$

This equation illustrates that pH depends on the ratio of metabolic (HCO_3^-) to respiratory (PaCO_2) components.

Stepwise Interpretation of ABG

Step 1: Assess pH

- $\text{pH} < 7.35 \rightarrow$ Acidosis
- $\text{pH} > 7.45 \rightarrow$ Alkalosis

Step 2: Evaluate PaCO₂

- Increased PaCO₂ → Respiratory acidosis
- Decreased PaCO₂ → Respiratory alkalosis

Step 3: Evaluate HCO₃⁻

- Decreased HCO₃⁻ → Metabolic acidosis
- Increased HCO₃⁻ → Metabolic alkalosis

Step 4: Determine Compensation

Assess whether physiological compensation is appropriate or if a mixed acid-base disorder is present.

Step 5: Evaluate Oxygenation

Interpret:

- PaO₂
- SaO₂
- Alveolar-arterial (A-a) gradient (when indicated)

Troubleshooting and Sources of Error in Arterial Blood Gas Analysis

Accurate arterial blood gas (ABG) results depend on strict adherence to standardized procedures during the pre-analytical, analytical, and post-analytical phases. Errors occurring at any stage may lead to inaccurate results, inappropriate interpretation, and incorrect clinical decisions. Understanding common sources of error and implementing effective troubleshooting strategies are essential components of quality assurance in clinical biochemistry laboratories.

Pre-Analytical Errors

The pre-analytical phase accounts for the majority of laboratory errors in ABG analysis.

Source of Error	Effect on Results	Troubleshooting
Air bubbles in the sample	↑ PaO ₂ , ↓ PaCO ₂ , ↑ pH	Expel air bubbles immediately after collection and cap the syringe securely.
Delay in sample analysis	↓ pH, ↑ PaCO ₂ , ↓ PaO ₂ due to continued cellular metabolism	Analyze the sample within 15 minutes or store on ice if a delay is unavoidable, following institutional protocols.
Inadequate heparin mixing	Formation of microclots, analyzer blockage, unreliable results	Gently roll and invert the syringe immediately after collection.
Excess liquid heparin	Dilution of the sample, falsely decreased electrolyte and blood gas values	Use pre-heparinized syringes with minimal balanced heparin.
Venous contamination	↓ PaO ₂ , ↑ PaCO ₂ , lower oxygen saturation	Confirm arterial puncture by observing pulsatile blood flow and bright red blood.
Hemolysis	Elevated potassium and altered biochemical parameters	Avoid excessive suction and rough handling of the specimen.
Incorrect patient identification	Reporting results for the wrong patient	Follow standard patient identification protocols before collection.

Analytical Errors

Analytical errors arise from instrument malfunction, calibration problems, or inadequate quality control.

Source of Error	Effect on Results	Troubleshooting
Improper calibration	Inaccurate measurement of all parameters	Perform scheduled automatic and manual calibration according to manufacturer recommendations.
Dirty or damaged electrodes	Unstable or erroneous readings	Clean, maintain, or replace electrodes regularly.
Expired reagents	Poor analytical accuracy	Monitor reagent expiration dates and replace as required.
Instrument drift	Gradual deviation in reported values	Perform routine internal quality control and preventive maintenance.
Blocked sample pathway	Error messages or incomplete analysis	Flush the analyzer and inspect for clots or debris.

Post-Analytical Errors

Source of Error	Effect	Troubleshooting
Data transcription errors	Incorrect patient report	Use electronic data transfer whenever possible and verify reports before release.
Misinterpretation of ABG results	Incorrect diagnosis or treatment	Interpret ABG findings in conjunction with the patient's clinical condition and laboratory data.
Failure to report critical values	Delay in patient management	Establish and follow institutional critical value notification policies.

Instrument Troubleshooting

Common analyzer problems and corrective actions include:

Problem	Possible Cause	Corrective Action
Calibration failure	Expired calibration solution, damaged electrodes	Replace calibration materials, inspect electrodes, and recalibrate.
Frequent clot detection	Inadequate sample mixing	Mix samples thoroughly immediately after collection.
Unexpected PaO ₂ values	Air contamination or oxygen therapy changes	Remove air bubbles, verify oxygen delivery settings, and repeat sampling if necessary.
Unstable pH readings	Electrode contamination or protein deposits	Clean or replace the pH electrode and perform quality control.
Analyzer error codes	Mechanical or electronic malfunction	Refer to the manufacturer's troubleshooting guide and contact technical support if required.

Quality Assurance Measures

To minimize errors and ensure reliable ABG results, laboratories should implement comprehensive quality assurance practices, including:

- Standardized specimen collection procedures.
- Use of balanced heparinized syringes.
- Proper staff training and competency assessment.
- Routine internal quality control (IQC).
- Participation in external quality assessment (EQA) or proficiency testing programs.
- Scheduled preventive maintenance of analyzers.
- Regular calibration verification.
- Documentation of corrective and preventive actions (CAPA).
- Compliance with Clinical and Laboratory Standards Institute (CLSI) and International Organization for Standardization (ISO 15189) guidelines.

Key Points for Reliable ABG Analysis

- Collect true arterial blood using aseptic technique.
- Perform the Allen test before radial artery puncture.
- Eliminate all air bubbles immediately after collection.
- Mix the specimen gently to prevent clot formation.
- Analyze samples promptly or store appropriately if delays are unavoidable.
- Perform daily quality control and routine instrument calibration.
- Interpret ABG findings together with clinical history, electrolyte values, lactate concentration, and other laboratory investigations.

Effective troubleshooting, adherence to quality management systems, and awareness of potential sources of error significantly improve the accuracy, precision, and clinical utility of arterial blood gas analysis.

Biochemical Classification of Acid-Base Disorders**Metabolic Acidosis****Biochemical Features**

- ↓ pH
- ↓ HCO_3^-
- Compensatory ↓ PaCO_2

Causes

- Diabetic ketoacidosis
- Lactic acidosis
- Renal failure
- Severe diarrhea
- Toxin ingestion

Biochemical Mechanism

Loss of bicarbonate or accumulation of non-volatile acids.

Metabolic Alkalosis**Biochemical Features**

- ↑ pH
- ↑ HCO_3^-
- Compensatory ↑ PaCO_2

Causes

- Persistent vomiting
- Diuretic therapy
- Excess bicarbonate administration
- Hyperaldosteronism

Respiratory Acidosis**Biochemical Features**

- ↓ pH
- ↑ PaCO_2
- Compensatory ↑ HCO_3^-

Causes

- Chronic obstructive pulmonary disease (COPD)
- Respiratory depression
- Neuromuscular disorders
- Airway obstruction

Respiratory Alkalosis**Biochemical Features**

- $\uparrow$ pH
- $\downarrow$ PaCO₂
- Compensatory $\downarrow$ HCO₃⁻

Causes

- Hyperventilation
- Anxiety
- Pulmonary embolism
- Sepsis
- Pregnancy

Role of Anion Gap

The anion gap helps classify metabolic acidosis.

Formula:

$$\text{Anion Gap} = \text{Na}^+ - (\text{Cl}^- + \text{HCO}_3^-)$$

Normal range:

8–12 mmol/L (without potassium)

High Anion Gap Acidosis

Examples include:

- Lactic acidosis
- Ketoacidosis
- Uremia
- Methanol poisoning
- Ethylene glycol poisoning

Normal Anion Gap Acidosis

Examples include:

- Diarrhea
- Renal tubular acidosis
- Acetazolamide therapy

Base Excess

Base excess quantifies the metabolic component independent of respiratory effects.

- Negative BE → Metabolic acidosis

- Positive BE → Metabolic alkalosis

It reflects the amount of acid or base required to return blood pH to normal under standardized conditions.

Lactate and Tissue Hypoxia

Serum lactate is a key biochemical marker measured with many modern blood gas analyzers.

Elevated lactate (>2 mmol/L) indicates impaired tissue oxygen delivery or utilization and is associated with:

- Septic shock
- Cardiogenic shock
- Trauma
- Hypoxia
- Severe anemia

Persistent hyperlactatemia is associated with increased mortality.

Clinical Applications of ABG

ABG analysis is routinely used in:

- Intensive Care Units (ICUs)
- Emergency medicine
- Pulmonary diseases
- Renal disorders
- Diabetic ketoacidosis
- Mechanical ventilation monitoring
- Sepsis management
- Poisoning and toxicology
- Perioperative monitoring

Laboratory Considerations

Accurate ABG interpretation requires adherence to pre-analytical and analytical quality standards. Important considerations include:

- Use of heparinized syringes
- Elimination of air bubbles
- Prompt analysis (within 15–30 minutes or storage on ice if delayed)
- Proper arterial sampling technique
- Regular analyzer calibration
- Internal and external quality control procedures

Common pre-analytical errors include delayed analysis, inadequate mixing, venous contamination, and exposure of the sample to air.

Recent Advances

Modern blood gas analyzers now integrate:

- Electrolyte analysis
- Lactate measurement
- Co-oximetry
- Hemoglobin fractions
- Point-of-care testing
- Automated acid-base interpretation

- Connectivity with laboratory information systems

These advancements enhance rapid clinical decision-making, particularly in emergency and critical care settings.

CONCLUSION

Arterial Blood Gas analysis is a powerful biochemical tool for assessing acid-base balance, respiratory function, and metabolic disturbances. Interpretation requires an understanding of the biochemical relationships between hydrogen ions, bicarbonate, and carbon dioxide, as described by the Henderson–Hasselbalch equation. Systematic evaluation of pH, PaCO₂, HCO₃⁻, oxygenation, base excess, lactate, and the anion gap enables accurate diagnosis of acid-base disorders and guides appropriate clinical management. Continued advances in point-of-care testing and integrated blood gas analyzers have further strengthened the role of ABG analysis in modern laboratory medicine and critical care [5-12].

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