Analysis of Arterial Blood Gases — A Comprehensive Approach

MS Barthwal

Abstract

The arterial blood gases is one of the most important investigations for assessment of clinical oxygenation and acid-base status in critically ill patients. It provides us with information about ventilation, oxygenation and acid-base status, the three closely interrelated physiology parameters, which maintain the pH homeostasis. Its correct interpretation and application necessitates the knowledge of basic applied physiology in relation to these parameters. Through this review article an attempt has been made to formulate a comprehensive approach by first describing the basic physiology in relation to these parameters followed by stepwise approach to analyse arterial blood gases.

INTRODUCTION

The analysis of arterial blood gases (ABG) plays a pivotal role in making correct diagnosis and deciding management strategies in critically ill patients. This role can be well exemplified by considering the concept of respiratory failure. This term remains nonspecific and does not help much in deciding whether the respiratory failure is due to primary oxygenation failure or ventilatory failure. ABG is the only investigation, which can document, specify and quantitate the respiratory failure. High PaCO₂, moderately low PaO₂, and acidic pH indicate ventilatory failure and low PaCO₂, low PaO₂ and alkaline pH indicate primary oxygenation failure. The management plan will be ventilatory support in the former case and oxygen therapy in the later case. Since ABG provides a rapid and accurate assessment of oxygenation, ventilatory and acid-base status, the prerequisite for understanding and correctly interpreting ABG provides a rapid and accurate assessment of oxygenation, ventilatory and acid-base status, the prerequisite for understanding and correctly interpreting ABG is knowledge of basic physiology in relation to ventilation, oxygenation and acid base status. Through this review an attempt has been made to formulate a comprehensive approach by first describing the basic physiology in relation to ABG, followed by stepwise approach to analyse ABG.

BASIC PHYSIOLOGY IN RELATION TO ABG

The ABG provides us with rapid information on following three physiologic processes, which maintain the pH homeostasis:

1. Alveolar ventilation
2. Oxygenation
3. Acid-base balance

These three processes are closely interrelated with each other and alteration in one process affects other process. For the sake of simplicity and better understanding the basic physiology in relation to each will be discussed separately avoiding the more complex details.

1. Alveolar ventilation: The maintenance of CO₂ level reflected by arterial CO₂ tension (PaCO₂) at any given moment depends on the quantity of CO₂ produced in body and its excretion through alveolar ventilation (Vₐ) and can be expressed by the equation, PaCO₂ ~ CO₂/Vₐ. The alveolar ventilation is that portion of total ventilation that participates in gas exchange with pulmonary blood. It is presumed that CO₂ production is constant, then CO₂ homeostasis can be simplified to 1/Vₐ ~ PaCO₂. Thus PaCO₂ is the best index for assessment of alveolar ventilation. High PaCO₂ (> 45 mmHg) indicates alveolar hypoventilation and low PaCO₂ (< 35 mmHg) implies alveolar hyperventilation.

2. Oxygenation: The ultimate aim of oxygenation is to provide adequate delivery of oxygen to tissues. This is a function of cardiopulmonary system and various factors like arterial oxygen tension (PaO₂), oxygen concentration of inspired air (FiO₂) and hemoglobin content with its affinity and saturation with oxygen contribute towards normal tissue oxygenation. The PaO₂ and SaO₂ is primarily used for assessment of oxygenation status since PaO₂ accurately assesses oxygenation from 30 to 200 mmHg, whereas SaO₂ is normally reliable only in the range of PaO₂ from 30 to 60 mmHg. Oxygen saturation measurement by pulse oximetry (SpO₂) or by ABG analysis (SaO₂) is better indicator of arterial oxygen content than PaO₂ since approximately 98% of oxygen...
is carried in blood in the combined state with hemoglobin. Hypoxemia is defined as PaO₂ of less than 80 mmHg at sea level in an adult patient breathing room air; the similar decrease in cells/tissues is known as hypoxia. The presence of hypoxia in hypoxemia depends on the severity of hypoxemia and the functioning of cardiovascular system. Hypoxia is unlikely in mild hypoxemia (PaO₂=60-79 mmHg). Moderate hypoxemia (PaO₂=45-59 mmHg) may be associated with hypoxia if cardiovascular system is malfunctioning. Hypoxia is almost always associated with severe hypoxemia (PaO₂ < 45 mmHg). the PaO₂ must always be interpreted in relation to concentration of inspired oxygen FiO₂ and age.

Relation between PaO₂ and FiO₂ : PaO₂ alone provides little information regarding efficiency of oxygen loading into the pulmonary capillary blood. In other words it does no quantitate the physiological shunt, which helps in assessment of the severity of underlying disease in lungs and in guiding oxygen therapy. There are various indices for calculation of physiological shunt, for example, classic shunt equation, which is the gold standard but requires mixed venous sampling through Swan-Ganz catheter and alveolar arterial oxygen gradient, which needs a bit calculation. The simplified and through Swan-Ganz catheter and alveolar arterial oxygen gradient, which needs a bit calculation. The simplified and clinically ratio (in which denominator FiO₂ is taken as %FiO₂).

Since the normal PaO₂ in an adult breathing room air with FiO₂ of 0.2 is 80 to 100 mmHg, the normal values for PaO₂/FiO₂ ratio or oxygenation ratio are 400-500 mmHg or 4.0 to 5.0 respectively. PaO₂/FiO₂ ratio of less than 200 most often indicates a shunt greater than 20%. A notable limitation of PaO₂ at low FiO₂ ratio is this that it does not take into account changes in PaCO₂ at low FiO₂, which tends to have a considerable effect on the ratio.

Age : The normal arterial oxygen tension decreases with age. Considering the normal PaO₂ more than 80 mmHg in an adult at sea level breathing room air, a general guideline is to subtract 1 mmHg from the lower limit and moderate hypoxemia. However, at any age PaO₂ of lesser than 40 mmHg indicates severe hypoxemia.

Acid-base Balance : The aim of regulating acid base balance is to maintain pH within a narrow range. The pH homeostasis is accomplished through the interaction of lungs, kidneys and blood buffers. This interaction is best represented by Henderson-Hasselbalch equation which describes the fixed inter-relationship between PaCO₂, pH and HCO₃⁻ and is described as pH = pKₐ - log HCO₃⁻/PaCO₂. If all the constants are removed, the equation can be simplified to pH=HCO₃⁻/PaCO₂ = Kidney/Lung. The HCO₃⁻ is controlled mainly by kidney and blood buffers. The lungs control the level of PACO₂ by regulating the level of volatile acid, carbonic acid, in the blood. There is a direct linear relationship between concentration of dissolved CO₂ and concentration of carbonic acid. The blood system in body is carbonic acid/bicarbonate base (H₂CO₃/HCO₃⁻). Buffer system can act within a fraction of a second to prevent excessive change in pH. Respiratory system takes about 1-15 minutes and kidneys many minutes to days to readjust H⁺ ions concentration.

(a) Indices for acid-base states : PaCO₂ is a clear and concise marker of respiratory acid-base disturbance. A rise in PaCO₂ always indicates increased carbonic acid and vice versa. The comparable metabolic index for metabolic acid-base disturbance does not exist and following indices are commonly used.

i) Plasma Bicarbonate (Actual bicarbonate) : The plasma bicarbonate is a commonly used indicator and is easily calculated from PaCO₂ and pH using Henderson-Hasselbalch equation. However, it is not a pure indicator of nonrespiratory acid-base problem since it increases in respiratory acid-base disturbance by virtue of hydrolysis reaction. The normal value of HCO₃⁻ is 24 ± 2 meq/l.

ii) Standard Bicarbonate : This is plasma bicarbonate obtained after the blood has been equilibrated at 37°C with a PaCO₂ of 40 mmHg. This should eliminate the hydrolysis effect, however, the standard bicarbonate manifests lower result due to the presence of hypercarbia.

iii) Buffer Base (BB) : Blood buffer base (BB) is the sum of all the buffer bases in a litre of blood. Thich can be sued as a metabolic index in exactly the same way as HCO₃⁻ is used. It is calculated from the measurement of pH, PaCO₂ and hematocrit and reported as meq/l of base above or below the normal buffer range. The negative base excess is often referred to as a base deficit. The normal value of BB is 0 ± 2 meq/L.

To sum up, for practical purposes any of these metabolic indices will provide adequate information and clinically appropriate interpretation.

Plasma pH and K⁺ : The distribution of potassium ion (K⁺) within intracellular and extracellular spaces affects acid-base balance. In acidemia, the excess of H⁺ ions are transported to the intracellular space and to maintain electroneutrality, K⁺ move out into the plasma leading to hyperkalemia. The reverse reaction takes place in alkalimia. In the distal renal tubule cell the potassium or hydrogen ion can be exchanged for sodium ion (Na⁺), depending on the body’s requirement. Hence in the presence of alkalosis, H⁺ ions are retained and K⁺ ions are exchanged for Na⁺ leading to development of hypokalemia.

Preparation for arterial sampling : Following points must be considered before obtaining sample to avoid errors in blood gas measurement.

a) Steady State : Blood sampling must be done during steady state whenever there is initiation or change in oxygen therapy or changes in ventilatory parameters with patients on mechanical ventilation. In the patients without overt pulmonary disease a steady state is reached between 3-10 minutes and in patients with chronic airways obstruction it takes about 20-30 minutes.

b) Anticoagulants : Excess of heparin may affect the pH. Only 0.05 ml is required to anticoagulate 1 ml of blood. Because dead space volume of a standard 5 ml syringe with 1 inch 22 guage needle is 0.02 ml, filling the syringe dead space with heparin provides sufficient volume to anticoagulate a 4 ml blood sample.

c) Delay in processing of sample : Because blood is a
living tissue, O\textsubscript{2} is being consumed and CO\textsubscript{2} is produced in the blood sample. The delay may affect the blood gas values. In case of delay, the sample should be placed in ice and such iced sample can be processed up to 2 hours without affecting the blood gas values.\textsuperscript{14}

d) Venous Sampling : Arterial blood provides more information than venous blood with regard to acid-base and oxygenation status. However venous blood from a well perfused patient may provide a gross indication of acid-base status but is unacceptable for oxygenation from a well perfused patient may provide a gross indication of acid-base status. However venous blood from a well perfused patient may provide a gross indication of acid-base status but is unacceptable for oxygenation status.\textsuperscript{15} Following points may help in recognizing inadvertent venous sampling :

i) Failure to observe a flash of blood on entry into vessel or pulsation during syringe filling

ii) Incompatibility of values with clinical condition

iii) Low PaO\textsubscript{2} and high PaCO\textsubscript{2}

iv) SpO\textsubscript{2} by pulse oximetry more than SaO\textsubscript{2} by ABG analysis

As a first resort the sampling may be done again while preferably simultaneously drawing a venous sample from same anatomic area for comparison.

The acceptable therapeutic ranges for blood gas parameters are :

\[
\text{PH}=7.35 - 7.45, \text{PaO}_2 = 80 - 100 \text{ mmHg}, \text{PaCO}_2 = 35 - 45 \text{ mmHg}, \text{HCO}_3^- = 24 \pm 2 \text{ meqL}, \text{BE} = 0 \pm 2 \text{ meq/L}
\]

Concept of compensation : Whenever an acid-base disturbance occurs it is followed by a compensatory response by respiratory system or kidneys depending upon the primary disturbance. Following are the rules of compensation :

**RULES OF COMPENSATION**

i) The compensatory response depends upon the proper functioning of organ system involved in the response (lungs or kidneys) and on the severity of acid-base disturbance. For example, the likelihood of complete compensation in chronic respiratory acidosis is less than 15% when PaCO\textsubscript{2} exceeds 60 mmHg.\textsuperscript{16}

ii) Acute compensation occurs within 6-24 hours and chronic within 1-4 days. Respiratory compensation occurs faster than metabolic compensation.

iii) In clinical practice it is uncommon to see complete compensation. The maximum compensatory response in more cases is associated with only 50% to 75% return of pH to normal.\textsuperscript{17} However, in chronic respiratory alkalosis the pH may actually return completely to normal in some cases.\textsuperscript{18}

**Expected compensation for simple acid-base disorders**\textsuperscript{19,20}

i) Metabolic acidosis : Expected PaCO\textsubscript{2} decreases by 1-1.3 mmHg for every 1 meq/L decrease in HCO\textsubscript{3}^- or expected PaCO\textsubscript{2} = last two digits of pH.

ii) Metabolic alkalosis : Expected PaCO\textsubscript{2} increases by 0.5 - 0.7 mmHg for every 1 meq/L increase in HCO\textsubscript{3}^- or expected PaCO\textsubscript{2} = last two digit of pH.

iii) Respiratory acidosis : In acute acidosis, HCO\textsubscript{3}^- increases by 1 meq/L for every 100 mmHg increase in PaCO\textsubscript{2}. In chronic acidosis, the acidosis, the HCO\textsubscript{3}^- increases by 3.5 meq/L for every 10 mmHg increase in PaCO\textsubscript{2}.

iv) Respiratory alkalosis : in acute alkalosis HCO\textsubscript{3}^- decreases by 2 meq/L for every 10 mmHg decrease in PaCO\textsubscript{2}. In chronic alkalosis HCO\textsubscript{3}^- decreases by 5 meq/L for every 10 mmHg decrease in PaCO\textsubscript{2}.

**STEPWISE APPROACH TO ABG ANALYSIS**

The following stepwise approach will help in correctly analysing simple acid-base disorders, in which there is only one primary acid-base disorder.

1) **Identify the primary problem** by looking at pH and classifying it as acidic (< 7.35) and alkalotic (> 7.45).

2) **Identify the cause of acidosis/alkalosis** by looking at respiratory (PaCO\textsubscript{2}) and metabolic (HCO\textsubscript{3}^-) indices.

3) **When the pH is in the normal range** and the primary problem is not obvious, one should assess which side of 7.4 the pH is on. If pH is < 7.4, i.e. on the lower side of normal range (7.35-7.40), then the primary problem is acidosis. If pH is > 7.4, i.e. on the upper side of normal range (7.40 - 7.45), then the primary problem is alkalosis. This reasoning is based on the concept that most of the time the compensatory response is never complete. If acidosis is a primary disturbance then the pH has been brought down to below 7.35 and the compensatory process will bring back the pH up to the lower side of normal range. The same logic stands true for alkalosis. However, when the pH is in the normal range this could also be because of mixed acid-base disturbance (two primary acid-base disorders). This has been elaborated further.

4) **Classify simple acid-base disorders** : By classifying the pH as acidic (< 7.35), alkalotic (> 7.45), lower normal range (7.35-7.40) and higher normal range (7.40-7.45) and considering the ventilatory parameter (PaCO\textsubscript{2}) and metabolic index (HCO\textsubscript{3}^- or BE), the simple acid base disorders can be classified into twelve primary acid-base disorders.

(a) pH < 7.35 (Acidosis)

- **Acute respiratory acidosis (Acute ventilatory failure)** : - PaCO\textsubscript{2} > 45 mm Hg, HCO\textsubscript{3}^-/BE - Normal.

- **Partially compensated respiratory acidosis** : - PaCO\textsubscript{2} > 45 mm Hg, HCO\textsubscript{3}^-/BE - increased.

- **Acute metabolic acidosis (Uncompensated)** : - PaCO\textsubscript{2} = 35-45 mm Hg, HCO\textsubscript{3}^-/BE - decreased.

- **Partially compensated metabolic acidosis** : - PaCO\textsubscript{2} < 35 mm Hg, HCO\textsubscript{3}^-/BE - decreased.

(b) pH < 7.45 (Alkalemia)

- **Partially compensated metabolic alkalosis** : - PaCO\textsubscript{2} > 45 mm Hg, HCO\textsubscript{3}^-/BE - increased. In an alert patient with intact central nervous system it is rare for PaCO\textsubscript{2} to rise above 60 mmHg in response to metabolic
alkalosis, however in obtunded patient the PaCO₂ may rise much higher.

(vi) **Metabolic alkalosis (Uncompensated)**: - PaCO₂ = 35-45 mmHg, HCO⁻₃/BE - increased.

(vii) **Acute respiratory alkalosis (Acute alveolar ventilation)**: - PaCO₂ < 35 mm Hg, HCO⁻₃/BE - Normal.

(viii) **Partially compensated respiratory alkalosis**: - PaCO₂ < 35 mmHg, HCO⁻₃/BE - decreased.

(c) pH 7.35 - 7.40 (Lower Normal Range)

(ix) **Compensated respiratory acidosis (Chronic ventilatory failure)**: - PaCO₂ > 45 mm Hg, HCO⁻₃/BE - increased

(x) **Compensated metabolic acidosis**: - PaCO₂ < 35 mm Hg, HCO⁻₃/BE decreased

(d) pH 7.40 - 7.45 (Higher Normal Range)

(xi) **Compensated respiratory alkalosis (Chronic alveolar hyperventilation)**: - PaCO₂ < 35, HCO⁻₃/BE - decreased.

(xii) **Compensated metabolic alkalosis**: - PaCO₂ > 45 mm Hg, HCO⁻₃/BE - increased.

(5) **Check compensatory response** for acute or chronic acid-base status and also for inappropriate compensation to detect covert mixed acid-base disorder.

(6) **Calculate anion gap**: In case of metabolic acidosis find out the anion gap (normal -12 ± 12 meq/L) to classify it into high anion gap acidosis or normal anion gap acidosis.

(7) **Assess hypoxemic state**: - As mentioned earlier PaO₂ must be assessed in conjunction with FiO₂ and age and oxygenation ratio should be calculated for assessment of severity of shunting.

**Mixed acid-base disorders** - Mixed acid-base disorders are characterized by presence of two or more primary acid-base disorders and are far from uncommon in the hospital setting. It is essential to identify these mixed disturbances by observing certain clues so that appropriate treatment can be initiated (Fig. 1).

**Fig. 1 : Stepwise to mixed acid-base analysis.**

(c) **pH 7.35 - 7.40** (Lower Normal Range)

(d) **pH 7.40 - 7.45** (Higher Normal Range)
then there is associated metabolic alkalosis and if actual pH is less than expected ± 0.03, then there is associated metabolic acidosis.10 The associated metabolic abnormality can be confirmed by corresponding changes in metabolic indices (HCO₃⁻ or base excess). This way internal congruity of ABG can also be confirmed and if values are not showing the corresponding changes then some technical errors needs to be excluded.

(b) Inappropriate Compensation: The compensation is never complete and inappropriate compensation can lead to detection of mixed disorder. Examine the PaCO₂ in metabolic acidosis and alkalosis to identify the presence of a respiratory acid-base disturbance. In metabolic acidosis if PaCO₂ is much higher than expected, then there is an additional respiratory acidosis and if PaCO₂ is much lower than expected then there is additional metabolic acidosis. Similarly in respiratory alkalosis if HCO₃⁻ is lower than expected, there is additional metabolic acidosis and if HCO₃⁻ is more than expected then there is additional metabolic alkalosis.

(c) Compare the increase in anion gap with the fall in HCO₃⁻ in plasma: In metabolic acidosis of increased anion gap type, the fall in HCO₃⁻ is generally equal to the rise in plasma anion gap. If the rise in plasma anion gap substantially exceeds the fall in HCO₃⁻, there is coexisting metabolic alkalosis.19 If the fall in HCO₃⁻ markedly exceeds the increase in anion gap, it is suggestive of normal anion gap and an increase anion gap types of metabolic acidosis.19

(d) Temporal inconsistencies: Maximum renal compensation takes 2-3 days. Whenever maximal compensation appears to have occurred almost instantaneously, suspect underlying mixed disorder.

(e) The clinical history, vital parameters and review of serial ABGs provide significant clues to mixed acid-base disorders.

Common settings of mixed acid-base disorders:

(i) Metabolic acidosis/Respiratory acidosis: Severe pulmonary edema, cardiopulmonary arrest.
(ii) Metabolic acidosis/Respiratory alkalosis: Renal failure with vomiting, severe liver disease.
(iii) Metabolic acidosis/Metabolic alkalosis: Renal failure with vomiting, alcoholic ketoacidosis with vomiting.
(iv) Metabolic alkalosis/Respiratory acidosis: COPD with vomiting or diuretics use.

To conclude, knowledge of basic physiology in relation to oxygenation, ventilation and acid-base status helps us in formulating a comprehensive approach to analyse ABG. ABG report is to be interpreted in relation to its internal congruity and compatibility with the patient’s clinical condition before making changes in therapeutic plan.

References

11. Mathews PJ. The validity of PaO₂ values 3.6 and 9 minutes after an FiO₂ change in mechanically ventilated heart surgery patients. Respir Care 1987;32:1029-34.