O₂-CO₂ diagram as a tool for comprehension of blood gas abnormalities

Sathya Subramani,¹ Praghalathan Kanthakumar,¹ Delinda Maneksh,³ Anita Sidharthan,⁴ Shoma V. Rao,² Vinodh Parasuraman,² and Elizabeth Tharion¹

¹Department of Physiology and ²Surgical Intensive Care Unit, Christian Medical College, Vellore, Tamilnadu; ³Department of Physiology, Dr. Somervell Memorial C.S.I. Medical College and Hospital, Karakonam, Kerala; and ⁴Department of Physiology, Travancore Medical College, Kerala, India

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The O₂-CO₂ diagram is an often neglected but very useful tool to understand the implications of arterial blood gas (ABG) analysis, which is a challenging concept not only to the undergraduate medical student but also to practicing clinicians. Here, we present a simplified description of the O₂-CO₂ diagram that was developed in all its elegance by Rahn and Fenn (6) and subsequently reviewed by others (2, 5).

The O₂-CO₂ diagram plots Pco₂ on the y-axis against Po₂ on the x-axis. Any set of values of Po₂ and Pco₂, whether in atmospheric air, tracheal (inspired) air, alveolar air, mixed expired air, arterial blood, or venous blood, can be plotted on this diagram. It will be appreciated at the end of this discussion that 1) there are certain physical limits to what combinations of O₂ and CO₂ can exist in the alveolus and, therefore, the blood; and 2) even if arterial blood gases are the only available laboratory parameters, one can make reasonable assumptions about alveolar gas composition and assess if a patient has a pure ventilatory defect or a diffusion defect; however, it is difficult to assess mixed disorders without direct measurement of alveolar gas partial pressures.

To begin, let us review the composition of atmospheric air, inspired air, and alveolar air (Fig. 1). Dry atmospheric air is composed of 21% O₂, with the rest N₂ and negligible CO₂. Therefore, Po₂ in dry atmospheric air at sea level is 21% of the atmospheric pressure (P atm) of 760 mmHg, which is 159 mmHg. As air passes through the upper airways during inspiration, it is saturated with water vapor, the partial pressure of which at body temperature, pressure, saturated (BTPS) is 47 mmHg. The addition of water vapor dilutes inspired air, thereby reducing both the partial pressure of nitrogen and Po₂ proportionally. The Po₂ in inspired air is therefore 149 mmHg [21% of (760 – 47) mmHg] and is henceforth represented as P̂o₂.

While the inspired air in the conducting zone is composed of N₂, O₂, and water vapor, a fourth gas, namely, CO₂, is added to alveolar air. Since the alveoli are open to the atmosphere and during either phase of respiration alveolar pressure is only slightly different from P atm, it is safe to assume that alveolar pressure at all times is almost equal to P atm or the total pressure of inspired air (760 mmHg).

The partial pressures of nitrogen (564 mmHg) and water vapor (47 mmHg) are almost the same in inspired and alveolar air. The remaining 149-mmHg pressure is due to O₂ alone in the inspired air (P̂o₂), whereas in the alveolus, the combined pressures of O₂ (PＡO₂) and CO₂ (PＡCO₂) must be close (but not necessarily equal1) to 149 mmHg. Since O₂ diffuses out of the alveolus, it is obvious that removal of O₂ and, therefore, reduction of its partial pressure compensates for the addition of CO₂.

The crude relationship is therefore as follows:

\[ \text{PＡO}_2 + \text{PＡCO}_2 = \text{P} \text{̂o}_2 \]

By rearranging the equation, we obtain the following:

\[ \text{PＡO}_2 = \text{P} \text{̂o}_2 - \text{PＡCO}_2 \]

The factors that affect PＡO₂ from the above equation are P̂o₂ and PＡCO₂. At steady state, in a normal individual breathing room air, P̂o₂ is 149 mmHg, and if PＡCO₂ is 40 mmHg, PＡO₂ can be as high as 109 mmHg.

However, in the normal resting state, the measured PＡO₂ (from end-expiratory air) is 100 mmHg when PＡCO₂ is 40 mmHg. Therefore, there must be other factors that affect PＡO₂.

Two other factors that should logically affect PＡO₂ are minute ventilation and the metabolic rate. PＡO₂ should vary directly with minute ventilation and inversely with metabolic rate. However, these two factors affect PＡCO₂ as well (in directions opposite to those of PＡO₂), and it has just been considered that PＡCO₂ itself is an important determinant of PＡO₂, since the sum of PＡO₂ and PＡCO₂ should not be very different from 149 mmHg. In addition, minute ventilation itself varies directly with metabolic rate. The influence of minute ventilation and metabolic rate being complex, their effects on PＡO₂ are best discussed in terms of a composite parameter, the respiratory quotient (RQ), which is the ratio of volume of CO₂ eliminated (representing ventilation) to volume of O₂ consumed (representing metabolism).

Fenn et al. (3) explained the relationship between PＡO₂ and its three determinants (namely, P̂o₂, PＡCO₂, and RQ) in the form of the alveolar gas equation. The simplified alveolar gas equation is as follows:

\[ \text{PＡO}_2 = \text{P} \text{̂o}_2 - \left(\text{PＡCO}_2 / \text{RQ}\right) \]

1 The explanation for this inequality is not considered in this report for reasons of simplicity. Interested readers are referred to Ref. 1.
2 Steady state here refers to a state where all the CO₂ produced due to oxidative metabolism of a substrate by the O₂ consumed (and only that CO₂) is eliminated.
3 Some authors prefer to use the term "respiratory exchange ratio" (RER) to refer to the ratio of volume of CO₂ eliminated to the volume of O₂ consumed and reserve the term "RQ" to refer to the ratio of volume of CO₂ produced to volume of O₂ consumed. Other authors use the term "R value" to refer to RER.
The general form of the simplified equation is as follows:

$$PAO_2 = FIO_2, dry \times (Patm - saturated \text{ water vapor pressure}) - (PACO_2/RQ)$$

[since $P_{O_2} = FIO_2, dry \times (Patm - saturated \text{ water vapor pressure})$, where $FIO_2, dry$ is the fraction of inspired $O_2 (FiO_2)$ in dry air.]

In room air at sea level, this equation reduces to the following:

$$PAO_2 = [0.21 \times (760 - 47)] - (PACO_2/RQ)$$

$$PAO_2 = 149 - (PACO_2/RQ)$$

If the individual is in steady state (and is not retaining $CO_2$ or eliminating more $CO_2$ than is produced), then $RQ$ is 0.8, with the valid assumption that the individual is metabolizing a mixture of carbohydrates, protein, and fat. The equation then reduces to the following:

$$PAO_2 = 149 - (PACO_2/0.8)$$

The physiological implication of the alveolar gas equation is that there is a limit on the possible $PAO_2$ and $PACO_2$ combinations that can exist in the alveolus. This limit will become evident after a discussion of the $O_2-CO_2$ diagram.

The clinical applications of the alveolar gas equation are twofold:

1. When both $PAO_2$ and $PACO_2$ are measurable clinically, $RQ$ can be calculated. An $RQ$ of $>0.8$ means that the subject is eliminating more $CO_2$ than is produced metabolically, and an $RQ$ of $<0.8$ means that the subject is retaining $CO_2$ ($RQ$ is discussed in greater detail later).

2. The alveolar gas equation can also be used to predict $PAO_2$ if $PACO_2$ is known (end-tidal $CO_2$ measurement with capnometry), assuming a steady-state $RQ$ of 0.8. Instrumentation to measure $PAO_2$ directly may not be available in all clinical settings.

Substitution of Arterial $PCO_2$ for $PACO_2$ in the Alveolar Gas Equation

When even capnometry (end-tidal $CO_2$ measurements) is not available to assess $PACO_2$, it is still possible to predict $PAO_2$ because $PACO_2 = arterial PCO_2 (PaCO_2)$ when total ventilation and perfusion are normal and when there is no right to left extrapulmonary shunt.

By substituting $PaCO_2$ for $PACO_2$ in the alveolar gas equation, we obtain the following:

$$PAO_2 = 149 - (PaCO_2/0.8)$$

Prediction of $PAO_2$ is important to assess if the arterial $PO_2 (PaO_2)$ is within its normal limits. A difference between $PAO_2$ and $PaO_2$ ($A-a O_2$ difference), when $>15$ mmHg in a young adult, suggests that $O_2$ diffusion is impaired due to diffusion membrane thickening, ventilation-perfusion ($V/Q$) mismatch, or right to left extrapulmonary shunt. It must be remembered that the $A-a O_2$ difference increases with age. A commonly used equation gives the normal $A-a O_2$ difference as $(age/4 + 4)$ mmHg. For example, in a 10-year-old subject the normal $A-a O_2$ difference would be 6.5 mmHg and in an 80-year-old subject it would be 24 mmHg.

The concepts stated above can be understood graphically with the $O_2-CO_2$ diagram, which is another major contribution from Fenn (and Rahn) (6), in addition to the alveolar gas equation.

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4 The general form of the equation is important in settings where $FiO_2$ can be different from 0.21, as in cases of $O_2$ supplementation, or when $Patm$ can be different, as in high altitude.

5 The term “shunt” used in respiratory physiology usually means the intrapulmonary shunt, which refers to blood passing through unventilated alveoli (ventilation/perfusion = 0). However, right to left extrapulmonary shunt (as in congenital heart diseases with right to left shunt) is equivalent to alveolar dead space, since it refers to blood bypassing ventilated alveoli and amounts to wasted ventilation (higher than normal ventilation/perfusion).
The O₂-CO₂ Diagram

The O₂-CO₂ diagram shown in Fig. 2 is a graph with Po₂ on the x-axis and Pco₂ on the y-axis. Any set of air gas values (open circles) or blood gas values (solid circles) can be plotted in this graph (Fig. 2).

In the O₂-CO₂ diagram shown in Fig. 2A, point S represents the composition of atmospheric air at sea level and point I represents the composition of inspired air (saturated with water vapor). The alveolar gas composition cannot be directly determined, but since the end-expiratory gas composition is very close to alveolar gas, the end-expiratory gas composition can be assayed, and the point plotted (point A). Point A₀.₈ represents reference values for the alveolar gas composition (100,40) at an RQ of 0.8.

The line connecting points I and A₀.₈ would be the alveolar gas line, at an RQ of 0.8. The implication of the alveolar gas equation is that alveolar gas values at a given RQ value can only fall along the alveolar gas line.

At an RQ of 1 (i.e., when the subject is not in steady state and is hyperventilating or if the subject is in steady state and is metabolizing a pure carbohydrate substrate), PAO₂ will be 110 mmHg while PA CO₂ is at 40 mmHg. This point is represented by point A₁.

It is to be noted that if the RQ is higher, the slope of the alveolar gas line would be steeper and PAO₂ would be greater for a given level of PA CO₂, and vice versa. The issues required to be clearly understood at this juncture are what RQ actually means and how it can be determined.

RQ is the ratio of volume of CO₂ eliminated by the lungs to the volume of O₂ consumed over a given time. In a normal reference individual at steady state, the volume of CO₂ eliminated in 1 min is 200 ml⁶ and that of O₂ consumed is 250 ml; hence, the RQ is 0.8. The term “RQ” is also used for the ratio of the volume of CO₂ produced in tissues during metabolism to the volume of O₂ consumed over a given time (hereafter the term RQ is used when the ratio is used to convey the second meaning). In this sense, when pure carbohydrates are metabolized, RQ is 1 and when pure fats are metabolized, RQ is 0.7. At steady state, all of and only the CO₂ produced metabolically is eliminated, and therefore RQ = RQ₁. Since the estimated RQ in a normal individual at steady state is 0.8 by measuring the volumes of the gases by indirect calorimetry, it is assumed that the individual is metabolizing a mixed substrate, given that RQ = RQ₂ at steady state.

While the volume of O₂ consumed in the lungs obviously equals the volume of O₂ used for metabolism by tissues over a given period, the same cannot be said of volume of CO₂ eliminated in the lungs and the volume of CO₂ produced in tissues over a given period. While at steady state, all the CO₂ produced is eliminated; there are situations where some of the CO₂ produced metabolically is retained and not completely eliminated (e.g., developing compensation for metabolic alkalosis) and other situations where more CO₂ is eliminated than is produced by oxidative metabolism of substrate (e.g., developing compensation for metabolic acidosis, where the excess that is eliminated comes not from oxidative metabolism but through the combination of anaerobically produced acids like lactic acid with bicarbonate reserves in the blood).

At an RQ of 0.8, ventilation is set to a level where it matches metabolism (RQ = RQ₁), i.e., all the CO₂ produced due to metabolism of the mixed substrate by the O₂ inhaled is being eliminated. If RQ > 0.8 (while RQ is still 0.8), it is inferred that ventilation is higher for the given metabolic rate, thereby eliminating more CO₂ than is produced by oxidative metabolism (of the mixed substrate), a typical example for the case being developing compensation for metabolic acidosis.

Once compensation is fully achieved and the organism is back to steady state where CO₂ elimination matches production (albeit with a lower PA CO₂ and therefore P ACO₂) RQ would become 0.8.

Graphically, the alveolar gas line in the O₂-CO₂ diagram (Fig. 2B) would shift right from the line for RQ = 0.8 to the line for RQ > 0.8 (while still pivoted on point I) during compensatory hyperventilation for metabolic acidosis. The alveolar gas point A would move to point B during active compensation for metabolic acidosis. Once compensation is achieved, the RQ would return to 0.8, and the alveolar gas point would move from point B to point A₉. Similarly, when there is hypoventilation (as in compensation for metabolic alkalosis), less CO₂ is eliminated than is produced by metabolism, so as to build P ACO₂ to a level sufficient to maintain pH. This would mean that the RQ would be <0.8, and, therefore, the alveolar gas line would shift left. The alveolar gas point would move from point A to point C. However, once PA CO₂ has been built up sufficiently and pH correction has occurred, no further CO₂ retention needs to occur. Ventilation returns to normal, and the alveolar gas line relaxes back to that at RQ = 0.8. The alveolar gas point would move from point C to point A₉.

Although the alveolar gas line would return to the reference line (RQ = 0.8) in compensated metabolic acidosis and alkalosis, the alveolar gas point would be lower down on the alveolar gas line in compensated metabolic acidosis (point A₉) and higher up in compensated metabolic alkalosis (point A₇), compared with the reference value (point A), which is (100,40). In other words, bicarbonate levels determine where along the alveolar gas line the alveolar gas point occurs.

It is important to appreciate that the slope of the alveolar gas line would be steeper than normal (and hence RQ > 1) only in cases of hyperventilation, where more CO₂ is being eliminated than is produced, e.g., in hyperventilation occurring as a compensation for metabolic acidosis as well as voluntary hyperventilation. In hyperventilatory states where the metabolic production of CO₂ itself is higher, and the hyperventilation has in fact occurred to eliminate just that excess CO₂ (so as to maintain pH) that is being produced, as in purely aerobic exercise, RQ would be near normal. Once the anaerobic threshold is reached, such as during exercise, and lactic acid begins to accumulate, ventilation would increase to eliminate more CO₂ than is produced so as to reduce PA CO₂ (for pH correction), and, thus, RQ would increase. After the exercise is stopped, RQ would be lower than normal.

⁶ These values can be obtained experimentally by indirect calorimetry.

⁷ Some authors prefer to use the term “hyperventilation” only to indicate conditions where the RQ is >1. For example, well-trained joggers may increase their minute ventilation from 5 to 30 liters during aerobic exercise, but if the end-tidal CO₂ (which reflects alveolar CO₂) and therefore the PAO₂ do not change, the RQ is still at 0.8, and the jogger is not hyperventilating!!!
Fig. 2. O₂-CO₂ diagram with the alveolar gas line representing the alveolar gas equation. Open circles represent air gas values, and solid circles represent blood gas values. A: the data points represent the composition of the following: atmospheric air (point S), inspired air saturated with water vapor (point I), alveolar air at an RQ of 0.8 (point A₀.₈), and alveolar air at an RQ of 1 (point A₁). The lines passing through points A₀.₈ and A₁ represent the alveolar gas lines at an RQ of 0.8 (dotted line) and 1 (solid line), respectively. B: the various alveolar gas points shown are representative of the following scenarios: reference values at an RQ of 0.8 (point A), ongoing compensation for metabolic acidosis with an RQ > 0.8 (point B), compensated metabolic acidosis when RQ reverts to 0.8 (point AB), compensation for metabolic alkalosis with CO₂ retention with an RQ > 0.8 (point C), and compensated metabolic alkalosis with an RQ = 0.8 (point AC). C: alveolar gas points during steady state in a normal individual (point A), with purely aerobic exercise (point b), with a low basal metabolic rate (point e), during voluntary hyperventilation (point a), during exercise beyond the anaerobic threshold (point c) and in the postanaerobic exercise period (point d). D: graphical method of determining whether the alveolar-arterial (A-a) O₂ difference is within the normal limits. The region bounded by the parallel lines passing through points A₀.₈ and A₁ represents the normal A-a O₂ difference. Note that there is impairment of O₂ diffusion at point G compared with point F, even though arterial PO₂ (PaO₂) at point G is much higher than that at point F. E: graphical method of predicting PₐO₂ (point Aₚₐ) from PₐO₂ (point Aₚₐ₉). The assumption here is that PₐCO₂ = PₐCO₂ and is valid when there is no right to left extrapulmonary shunt. F: arterial blood gas values of humans at different levels of fraction of inspired O₂ (FIO₂). Note that while values at FIO₂ of 35% and 60% are plotted on the graph, the alveolar gas line shown is the reference alveolar gas line (FIO₂ of 21%).
lactic acid is aerobically converted to CO₂. All of this CO₂ derived from oxidative metabolism is not eliminated for two reasons: 1) part of it is converted to bicarbonate in the kidney to replenish the bicarbonate reserves and 2) part of it is retained as dissolved CO₂ to match the increase in bicarbonate. This would lead to a low RQ, even <0.6 (4).

The discussion above can be best understood if one considers what changes would happen to alveolar gas point \( A \) from normal in an individual under the following circumstances (see Fig. 2C for answers):

- a. Voluntary hyperventilation
- b. Purely aerobic exercise
- c. Exercise at a rate beyond the anaerobic threshold
- d. Postanerobic exercise while the O₂ debt is being paid
- e. Reduced basal metabolic rate, as in hypothermia or hypothyroidism

**The O₂-CO₂ Diagram in Clinical Practice**

A base diagram (Fig. 2D) can be prepared with points \( I \) and \( A_{O,8} \). Points \( I \) and \( A_{O,8} \) can be connected to get the reference alveolar gas line with RQ = 0.8. The gases in end-expiratory air (which reflects alveolar air) are estimated and used to plot the patient’s alveolar gas point \( A_{pat} \) (103,44)). The patient’s true alveolar gas line can be obtained by connecting points \( I \) and \( A_{pat} \). If the patient’s true alveolar gas line falls to the right of the reference alveolar gas line, then it must be inferred that the patient is actively compensating for metabolic acidosis or is hyperventilating, due to either hysteria or ventilator settings. If the patient-specific alveolar gas line falls to the left of the reference alveolar gas line, then there is either progressive respiratory depression or on-going compensation for metabolic acidosis. Another line representing the normal upper limit of the A-a O₂ difference can be drawn as follows.

First, calculate the upper limit of the A-a O₂ difference as (age/4 + 4) mmHg. For example, in a subject of 32 yr of age, the A-a O₂ difference must be <32/4 + 4 = 12 mmHg. Plot point \( a_t \) = (103 - 12, 44). Draw a line passing through point \( a_t \) parallel to line \( I-A_{pat} \).

When ABG values are obtained, the arterial blood gas point (point \( a_{pat} \)) can be plotted on the graph. If point \( a_{pat} \) falls between the two parallel lines \( I-A_{pat} \) and the line passing through \( a_t \), O₂ diffusion is normal. If it falls to the left of this range, then the A-a O₂ difference is higher than normal for that age. (The horizontal line \( A_{pat}-a_{pat} \) represents the A-a O₂ difference.)

The A-a O₂ difference will be increased in the following situations:

1. Increased thickness of the respiratory membrane (diffusion defect), as in alveolar edema or fibrosis
2. Abnormal V/Q distribution
3. Right to left extrapulmonary shunt. In cases 1 and 2, the line \( A_{pat}-a_{pat} \) will be horizontal, but in the case of right to left extrapulmonary shunt, point \( a_{pat} \) will be above and to the left of point \( A_{pat} \), since there will be a significant alveolar-arterial CO₂ difference as well.

**Example question.** For a 32-yr-old individual, consider two points: point \( F \) (with \( P_{O_{2}} = 55 \text{ mmHg} \)) and point \( G \) (with \( P_{O_{2}} = 90 \text{ mmHg} \)). In which situation is there an O₂ diffusion defect (see Fig. 2D)?

**If End-Expiratory Gas Values Are Not Available**

If end-expiratory gas values are not available, and the only available laboratory parameters are ABG values, it is still possible to assess the A-a O₂ difference, as follows. First, ventilation is considered to be at steady state, and the reference alveolar gas line (at RQ = 0.8) is used. A new patient-specific alveolar gas point (point \( A_{pat} \)) must be plotted along the reference alveolar gas line at the same horizontal level as point \( a_{pat} \) (Fig. 2E). The assumption here is that \( P_{aCO_{2}} \) must be equal to \( P_{aCO_{2}} \); this is valid only if there is no right to left extrapulmonary shunt. The plotting of point \( A_{pat} \) in the way mentioned above is the graphical outcome of the alveolar gas equation. It can now be assessed if the A-a O₂ difference is within the normal range.

If point \( a_{pat} \) falls to the right of the reference alveolar gas line, then there is bound to be hyperventilation.

**Representation of Respiratory Failure in the O₂-CO₂ Diagram**

The O₂-CO₂ diagram can be divided in to three horizontal zones (Fig. 3) based on \( P_{CO_{2}} \) as follows: an upper zone, with \( P_{CO_{2}} > 50 \text{ mmHg} \); a middle zone, with \( P_{CO_{2}} \) between 50 and 35 mmHg; and a lower zone, with \( P_{CO_{2}} < 35 \text{ mmHg} \). It can be again divided into left, middle, and right zones by two vertical lines at \( P_{O_{2}} \) of 60 and 100 mmHg.

For normal metabolism to occur, \( P_{aO_{2}} \) must be maintained above 60 mmHg, and for blood pH to be maintained in its normal range, \( P_{aCO_{2}} \) must be between 35 and 50 mmHg, if serum bicarbonate is around its normal value of 25 meq/l.

In the \( P_{O_{2}}-P_{CO_{2}} \) diagram (Fig. 3), the space between the vertical lines at \( P_{O_{2}} = 100 \text{ and } 60 \text{ mmHg} \) represent the zone of normoxemia. Similarly, the space between the two horizontal lines at \( P_{CO_{2}} = 35 \text{ and } 50 \text{ mmHg} \) represent the range of normocarbia. The alveolar gas line that is drawn is the reference line for RQ = 0.8 and \( P_{O_{2}} \) (point \( I \)) = 149 mmHg. (The patient-specific alveolar gas lines should be drawn if the end-expiratory gas values are known; they may be steeper or less steep than the reference line.) The darkest shaded area within the normal ranges for \( P_{O_{2}} \) and \( P_{CO_{2}} \), bounded by the alveolar gas line and the age-specific line representing the normal limit of the A-a O₂ difference, is the range in which normal ABG values must fall. The age-specific line shown in Fig. 3 is for a 64-yr-old individual whose upper limit of A-a O₂ difference is 20 mmHg.

When there is a decrease in \( P_{aO_{2}} \) to < 60 mmHg or an increase in \( P_{aCO_{2}} \) to >50 mmHg, respiratory failure is said to have occurred. Respiratory failure can be classified as type I or type II. In type I respiratory failure, there is hypoxemia, and \( CO_{2} \) levels are normal or below normal. Type II respiratory failure refers to a condition where there is hypercarbia, often associated with hypoxia.

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8 There is an O₂ diffusion abnormality only in the case of point \( G \), because the point falls to the left of the line passing through point \( a_t \). In the case of point \( F \), the hypoxia is due to the limits on alveolar O₂ imposed by hyperventilation. Fenn calls this “hypercapneic hypoxia.” It is also called “obligatory hypoxia.”
**Type I respiratory failure.** As shown in Fig. 3, ABG values in the region filled with hatched lines represent type I respiratory failure (hypoxemia with normocarbia or hypocarbia). The primary pathology in type I respiratory failure is hypoxemia, and the hypocarbia, if it exists, is the result of increased ventilation due to the hypoxic drive. The causes for type I respiratory failure include those that will lead to a low PaO₂, whereas minute ventilation is normal or above normal, and, therefore, PaCO₂ is not high. These can be classified as follows:

1. Low PtO₂ due to low Patm (e.g., high altitude)
2. Low PtO₂ due to a reduced PtO₂ (e.g., breathing of air filled with smoke)
3. Regional inequalities of the V/Q while total ventilation and perfusion are normal (e.g., pneumonia or obstructed bronchus)
4. Diffusion abnormality due to a reduction in the surface area available for exchange (e.g., emphysema) or thickening of the respiratory membrane (e.g., fibrosis, interstitial or alveolar edema).

In cases 1 and 2, point I is shifted to the left, and the A-a O₂ difference can be normal; however, in cases 3 and 4, points I and A are normal, and the A-a O₂ difference can be high.

**Hypercarbia and type II respiratory failure.** PaCO₂ > 50 mmHg is considered to be hypercarbia. For normal arterial CO₂ levels to be maintained, 1) CO₂ must be delivered to the alveolus by perfusion, 2) CO₂ must diffuse across the alveolar membrane adequately, and 3) alveolar CO₂ must be cleared at a sufficient rate by the ventilatory mechanism.

Diffusion of CO₂ across the alveolar membrane is extremely fast and usually not compromised, even if there is lung disease. Therefore, hypercarbia occurs 1) in perfusion defects when all the venous CO₂ is not delivered to the alveoli, as in right to left extrapulmonary shunt; or 2) when ventilation is inadequate.

Ventilation is dependent on the normalcy of the following factors: brain stem respiratory centers, chemoreceptor sensitivity, muscles of respiration, upper and lower motoneurons concerned with muscles of respiration, neuromuscular junction, and the airways.

Hypoventilation secondary to diseases affecting the above components of the respiratory mechanism will lead to ABG values falling in the grid-lined region in Fig. 3,⁹ which represents type II respiratory failure.

It is easy to appreciate that type II respiratory failure as per the graph (Fig. 3) can be considered as type II failure without O₂ diffusion defects (grid-lined region with dots, where the A-a O₂ difference is within the normal range) and that with O₂ diffusion defects (grid-lined region without dots).

Caution must be exercised, however, in diagnosing an O₂ diffusion defect in type II respiratory failure using the reference alveolar gas line, because respiratory depression itself (if progressive) can cause a low RQ and the alveolar gas line may be shifted left. If alveolar gas values are available, the A-a O₂ difference can be easily assessed.

The unshaded area in the lower and middle zones in Fig. 3 represents situations where there is no clinical hypoxemia. However, if ABG values fall in this region, it must be inferred that there is an O₂ diffusion defect where PaO₂ is not high enough given the existing PaO₂.

**Occurrence of ABG Points to the Right of the Reference Alveolar Gas Line**

The following scenarios must be considered if the ABG points occur to the right of the reference alveolar gas line

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⁹ It must be remembered that in metabolic alkalosis as well, compensatory hypoventilation may result in blood gas values occurring in the grid-lined region in Fig. 3.
(when the true alveolar gas line cannot be constructed due to lack of alveolar gas values).

**Hyperventilation.** ABG points fall to the right of the reference alveolar gas line in the lower zone, in hyperventilation (whether voluntary or due to hysteria or mechanical ventilation). However, it must be reiterated that during hyperventilation, RQ will be higher, and the ABG point will still be to the left of the true alveolar gas line, if it can be drawn.

**Right to left extrapulmonary shunt.** In the case of right to left extrapulmonary shunts, the ABG point can occur in the areas above \( \text{PaCO}_2 \) = 40 mmHg and \( \text{PO}_2 \) = 100 mmHg, including the region to the right of the reference alveolar gas line in the areas mentioned. If alveolar gas values are available, the ABG point is to the left of and above the alveolar gas point and the slope of the true alveolar gas line is steeper. However, the slope does not reflect RQ in this condition. A subject with right to left extrapulmonary shunt will hyperventilate to maintain \( \text{PaCO}_2 \) even at an RQ of 0.8. This subject’s minute ventilation and \( \text{PAO}_2 \) would be higher than normal. The slope of the alveolar gas line would therefore be steeper even at the RQ of 0.8.

**Supplemental \( \text{O}_2 \).** The major scenario in which ABG points will fall to the right of the reference alveolar gas line in the middle zone is during the administration of supplemental \( \text{O}_2 \) in respiratory failure. In type I respiratory failure, with patients on supplemental \( \text{O}_2 \) and breathing voluntarily, the ABG points remain under the horizontal line at \( \text{PaCO}_2 \) = 50 mmHg. Chemosensitivity of the respiratory center is intact in these patients, and ventilation is not permitted to decrease to a level where \( \text{PaCO}_2 \) can increase above 50 mmHg. ABG values obtained from a surgical intensive care unit are plotted in Fig. 2F to illustrate the case. The other scenario where points can fall in the middle zone to the right of the reference alveolar gas line is in type II respiratory failure patients on mechanical ventilation and \( \text{O}_2 \) supplementation. However, it should be remembered that the true alveolar gas line with \( \text{O}_2 \) supplementation would still be to the right of the ABG point, since \( \text{PtO}_2 \) and, therefore, point 1 would be >149 mmHg.

One dangerous possibility when an ABG point occurs in the right upper zone is that a patient in chronic type II respiratory failure has presented with an acute exacerbation and has been given \( \text{O}_2 \) supplementation inadvertently without mechanical ventilation. The high \( \text{PaO}_2 \) removes the hypoxic drive, and ventilatory arrest can ensue.

At this juncture, it is worthwhile to reinforce the concept that \( \text{O}_2 \) supplementation will only cause a rightward shift of the ABG point. Mechanical ventilation, on the other hand, can result in two changes: 1) it can cause a downward shift of the ABG point and 2) it can change the RQ.

**Air bubble in the arterial sample.** An air bubble in the blood sample can give rise to spuriously high \( \text{PO}_2 \) values and therefore shift the gas point to right of the reference alveolar gas line, which is not a true reflection of the blood sample.

**Mixed Venous Blood Gas Point**

If there is a pulmonary artery catheter, then the mixed venous blood can be sampled (central vein sample can serve as a surrogate for mixed venous blood), and the gases can be estimated. Point \( v \), which represents mixed venous blood, can be plotted on the \( \text{O}_2\text{-CO}_2 \) diagram, and inferences can be drawn as to the adequacy of tissue perfusion. The arteriovenous \( \text{O}_2 \) difference at rest, if \( >60 \) mmHg, represents reduced tissue perfusion and, therefore, a low cardiac output. If it is less than normal, it implies mitochondrial failure or arteriovenous shunting, as in sepsis.

It is evident from the above discussion that the \( \text{O}_2\text{-CO}_2 \) diagram remains unsurpassed in its brilliance as a graphic depiction of gas exchange in the lungs in most clinical scenarios and is an easy tool to handle at the bedside.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).

**REFERENCES**