Chapter

Who Is Balancing: Is It RBC or Acid-Base Status?

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Abstract

Hemoglobin is an important intracellular protein buffer present inside the red blood cells (RBC). When the partial pressure of carbon dioxide (pCO_2) is increased, it freely diffuses into the RBC where it reacts with water molecules to form carbonic acid which dissociates to form bicarbonate and hydrogen ions by the enzyme carbonic anhydrase. Hydrogen ions liberated in this reaction are buffered by hemoglobin. Oxyhemoglobin is a stronger acid than deoxyhemoglobin. Oxygenation of hemoglobin causes an increase in net titratable hydrogen ion due to the Haldane effect. As the oxygen saturation of hemoglobin (sO_2) increases, the base excess is changed in the acidic direction, or as the sO_2 decreases, the base excess is changed in alkaline direction. The changes in the level of the enzyme carbonic anhydrase in RBC are related to the changes in pH, pCO_2, and bicarbonate levels in the blood. The understanding of the acid-base balance is a challenging task, but at the same time, it has immense clinical value. The relationship of carbonic anhydrase enzyme present inside the RBC in maintaining the acid-base balance to the commonly employed arterial blood gas (ABG) parameters like pH, pCO_2 bicarbonate, and base excess may help us for better understanding.

Keywords: acid-base balance, carbonic anhydrase enzyme, oxygen saturation, hemoglobin

1. Introduction

Arterial blood gas (ABG) analysis plays a vital role in the management of intensive care unit patients, especially for critically ill patients, but the interpretation is sometimes a challenging task especially if the acid-base disturbances are complex [1–5]. In ABG analysis, the pH and pCO_2 are measured parameters, but bicarbonate concentration is a calculated parameter derived from the modified Henderson equation [2]. Davenport or bicarbonate-pH diagram is a graphical tool representing the relationship between pH, pCO_2, and bicarbonate to depict the respiratory and metabolic acid-base disturbances. This Davenport diagram is rarely used in clinical setting [1].

Simple acid-base disorders are very easy to diagnose, but combined acid-base disorders due to either *compensatory* mechanisms or *mixed disorders* are often difficult and sometimes confusing. The *four acid-base disorders* are metabolic acidosis, metabolic alkalosis, respiratory acidosis, and respiratory alkalosis. Simple acid-base disorder is the presence of any of the four disorders with appropriate compensations. *Mixed acid-base disorder* denotes the presence of more than one primary disturbances which can be suspected from a lesser or greater than expected compensations. *Respiratory disorders* are associated with appropriate renal compensatory mechanisms, and similarly metabolic disorders are compensated by respiratory mechanisms [6, 7].

Base excess is defined as the amount of strong acid that must be added to each liter of fully oxygenated blood to return the pH to 7.40 at a temperature of 37°C and a pCO_2 of 40 mmHg. The normal level for base excess is −2 to +2 mEq/L. A negative base excess indicates the presence of base deficit. Actual base excess is the base excess of the blood, while standard base excess is the base excess of the *extracellular fluid (ECF)* at hemoglobin concentration of 5 gm/dL [8–10].

Under *normal ventilation*, bicarbonate parameter is useful, but in patients with abnormal ventilation (respiration), it may not reflect the true status because bicarbonate is a dependent variable and it changes with the concentration of pCO_2. As *pCO_2* increases, it reacts with *water molecules* to form *carbonic acid* which dissociates into *hydrogen* and *bicarbonate* ions. The hydrogen ions are buffered by *non-bicarbonate buffers* like albumin, hemoglobin, and phosphate buffer system. So, the concentration of bicarbonate increases as pCO_2 also increases. This *problem is solved by* measuring standard bicarbonate [11, 12].

Standard bicarbonate is the concentration of bicarbonate in the plasma from blood which is equilibrated with a normal pCO_2 (40 mmHg) and a normal pO_2 (over 100 mmHg) at a normal temperature (37°C). The *actual bicarbonate* and the *standard bicarbonate* concentrations are approximately equal under normal ventilation, but in abnormal respiration (either hypoventilation or hyperventilation), the two values alter and deviate from each other depending on the changes in the concentration of pCO_2 [1].

The bicarbonate value is increased in respiratory acidosis and decreased in respiratory alkalosis. So, the difference between bicarbonate and standard bicarbonate value is positive for respiratory acidosis and negative for respiratory alkalosis. If the acid-base disorder is purely metabolic without respiratory compensation, then the bicarbonate and standard bicarbonate values are more or less closer. If the metabolic disorder is compensated by respiratory mechanisms, then the two values alter and deviate from each other.

The most commonly used approach for arterial blood gas (ABG) analysis interpretation is a physiological approach based on the bicarbonate-carbon dioxide buffer system. The major buffer system in the ECF is the carbon dioxide-bicarbonate buffer system, and other buffer systems that play a role in buffering are protein and phosphate buffer systems. The buffers are substances that resist changes in pH. All buffers in a common solution are in equilibrium with the same hydrogen ion concentration. Therefore, whenever there is a change in hydrogen ion concentration in the extracellular fluid, the balance of all the buffer systems changes at the same time. This phenomenon is called the isohydric principle. Henderson-Hasselbalch equation concentrating on the bicarbonate-pCO_2 buffer is based on this principle. This approach is very simple and easier, but a major drawback of this is it is unable to quantify the metabolic (non-respiratory) component and does not explain the causative mechanism of metabolic acid-base disturbances [8].

2. Base excess

Base excess approach was developed to quantify the metabolic component, but it was *criticized* because it represents the whole blood and *did not* accurately *represent* the *whole body behavior*. Blood volume diluted with interstitial fluid represents the effective extracellular fluid hemoglobin concentration of 5 g/dl. *Standard base excess* or extracellular base excess is the base excess at hemoglobin concentration of 5 g/dl [8–12].

Oxyhemoglobin is a stronger acid than deoxyhemoglobin. Oxygenation of hemoglobin causes an increase in net titratable hydrogen ion because hydrogen ions are liberated from the oxygen-linked buffer groups due to the Haldane effect. So, the variation of oxygen saturation of hemoglobin (sO_2) influences the base excess result. The formula for calculating this is

$$\mathrm{cBase}(\mathrm{B}, \mathrm{oxygenated}) = \mathrm{cBase}(\mathrm{B}, \mathrm{actual}) - 0.2 \times \mathrm{ctHb} \times (1 - \mathrm{sO_2})$$

or

$$cBase(B, actual) = cBase(B, oxygenated) + 0.2 \times ctHb \times (1 - sO_2)$$

As the sO_2 increases, the term $0.2 \times \mathrm{ctHb} \times (1 - \mathrm{sO_2})$ decreases, so the base excess is changed in the acidotic direction because it is slightly decreased, or as the sO_2 decreases, the term $0.2 \times \mathrm{ctHb} \times (1 - \mathrm{sO_2})$ increases, so the base excess is changed in alkaline direction because it is slightly increased [8–10].

The correlation between pCO_2 and (HCO_3 − standard HCO_3)/H_2CO_3 and pCO_2 and ratio of (HCO_3/standard HCO_3) is clearly shown in **Figures 1** and **2**, respectively. From that, it is very clear that as the pCO_2 decreases, the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 also decreases and, as the pCO_2 increases, the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 also increases and, thereafter, the curve flattens. At pCO_2 of 40 mmHg, the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 is zero because the difference between bicarbonate and standard bicarbonate value is zero (HCO_3 − standard HCO_3 is zero). In respiratory acidosis (due to hypoventilation), pCO_2 retention occurs, and in respiratory alkalosis (due to hyperventilation), the pCO_2 value is decreased. The ratio of (HCO_3 − standard HCO_3)/H_2CO_3 changes in respiratory disorders and also in metabolic acid-base disturbances associated with respiratory compensations. The ratio of (HCO_3 − standard HCO_3)/H_2CO_3 is greater positive for respiratory acidosis and greater negative for respiratory alkalosis [1].

The normal range for standard base excess is ±2 mmol/L. If the value is >2 mmol/L, then it denotes metabolic alkalosis, and if the value is <−2 mmol/L, then it denotes metabolic acidosis (base deficit). Using this concept a four-quadrant graphical tool can be constructed for ABG interpretation using standard base excess

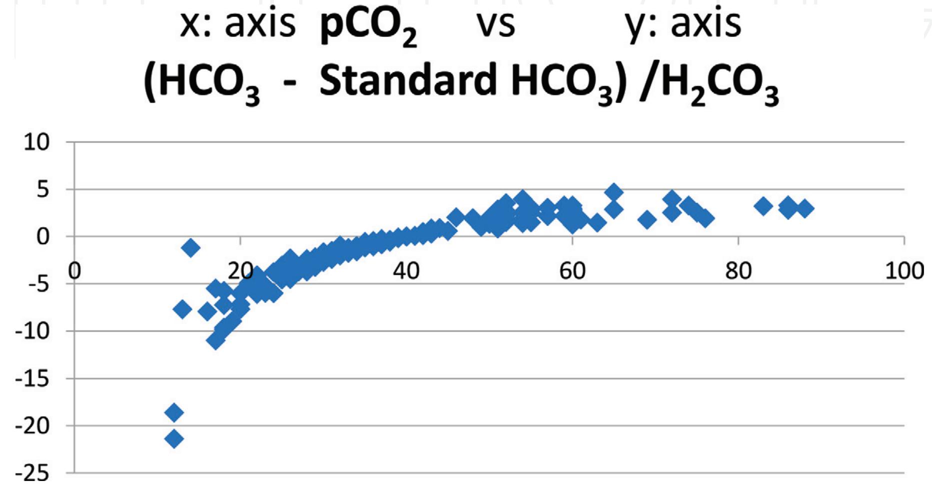

Figure 1.
Relation between pCO_2 and (HCO_3 − standard HCO_3)/H_2CO_3.

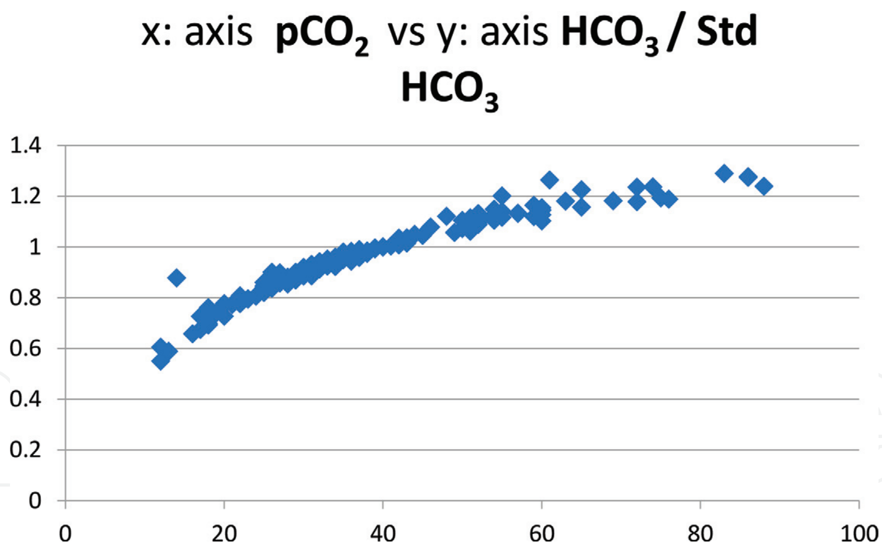

Figure 2.
Relation between pCO_2 and HCO_3/Std HCO_3.

and the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 in the two axes that demarcate the various acid-base disturbances which are shown in **Figure 3** [1].

The aim of the manuscript is to increase in depth the understanding of the acid-base balance which is a challenging and at times an arduous task, yet it has immense

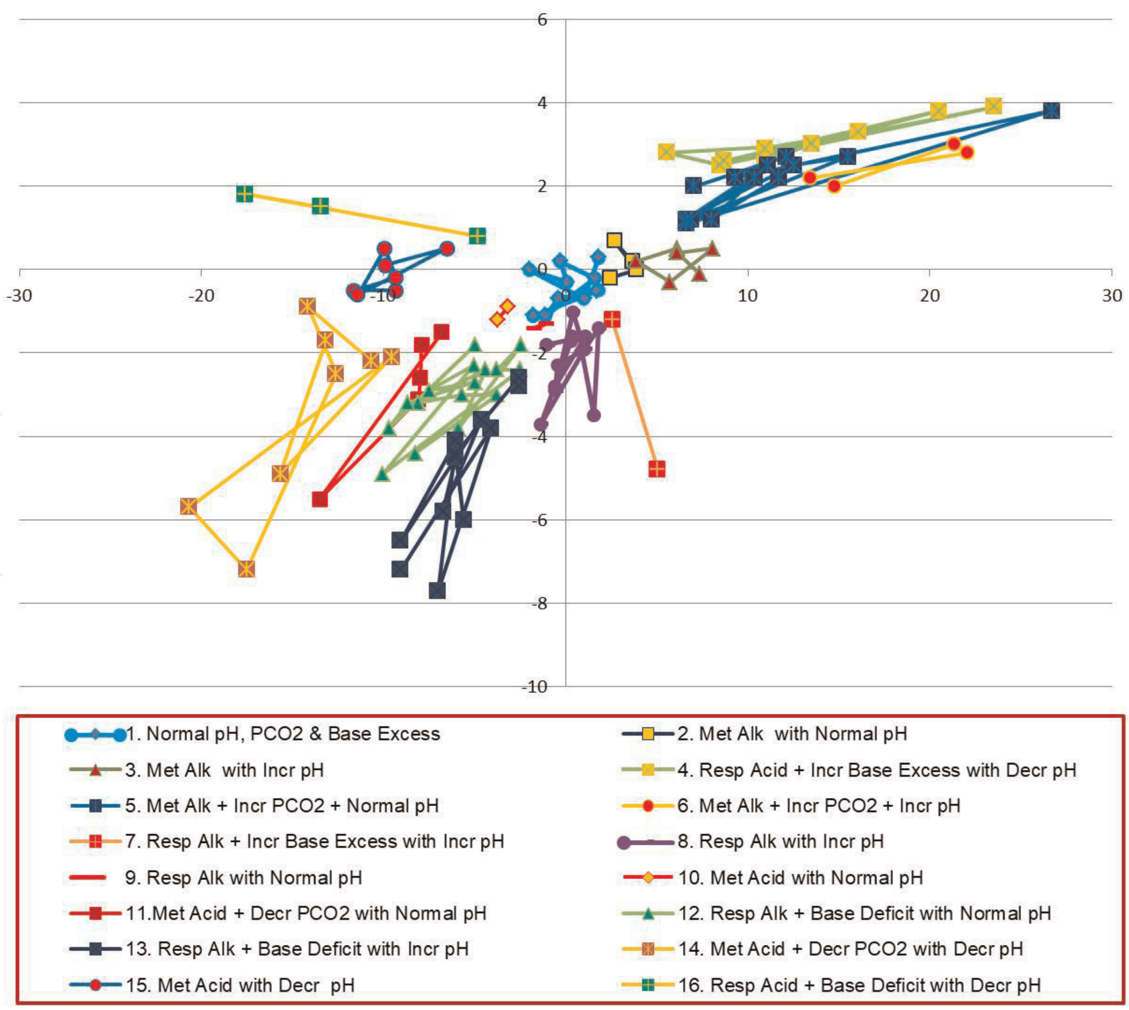

Figure 3.
Analysis of various acid-base disturbances using standard base excess (x-axis) and the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 (y-axis) in the four-quadrant graph.

clinical value. The relationship of the formation of bicarbonate from pCO_2 with the help of carbonic anhydrase enzyme present inside the RBC plays a significant role in maintaining the acid-base balance. The application of standard bicarbonate in the calculation of non-respiratory hydrogen ion concentration and development of a novel four quadrant graphical method for arterial blood gas interpretation may help us for better understanding.

3. Materials and methods

About 188 arterial blood gas sample data were utilized. Strict precautions were taken to avoid pre-analytical errors, and the consistency of the ABG report was checked by using the modified Henderson equation [2].

The main parameters like measured *pH*, pCO_2, HCO_3, *standard* HCO_3, and *standard base excess* values were noted. *Carbonic acid* concentration was calculated from pCO_2. The difference between bicarbonate and standard bicarbonate was calculated. The ratio of $(HCO_3 - \text{standard } HCO_3)/H_2CO_3$ was calculated [1].

Calculation of H^+*:*

H^+—hydrogen ion concentration at actual pH
(Calculated using *modified Henderson equation*)
H^+ (hydrogen ion concentration) = $\{24 \times pCO_2\}/HCO_3$
$pH = -log[H^+ \; nanomoles/L]$
$= -\log\,[H^+ \times 10^{-9} \text{ moles/L}]$
$= -\log\,[H^+] - \log\,[10^{-9}]$ $\{\text{nanomoles/L} = 10^{-9} \text{ moles/L}\}$
$pH = 9 - log\,[H^+]$

Calculation of NRH^+ *(non-respiratory hydrogen ion concentration):*

NRH^+—hydrogen ion concentration at non-respiratory pH
(At pCO_2 of 40 mmHg)

This calculated hydrogen ion concentration equivalent of standard bicarbonate has thus been called the "non-respiratory" hydrogen ion concentration or NRH^+ [13, 14]. It has a unique value for a given standard bicarbonate concentration, and the relationship is clearly shown in **Figure 4**:

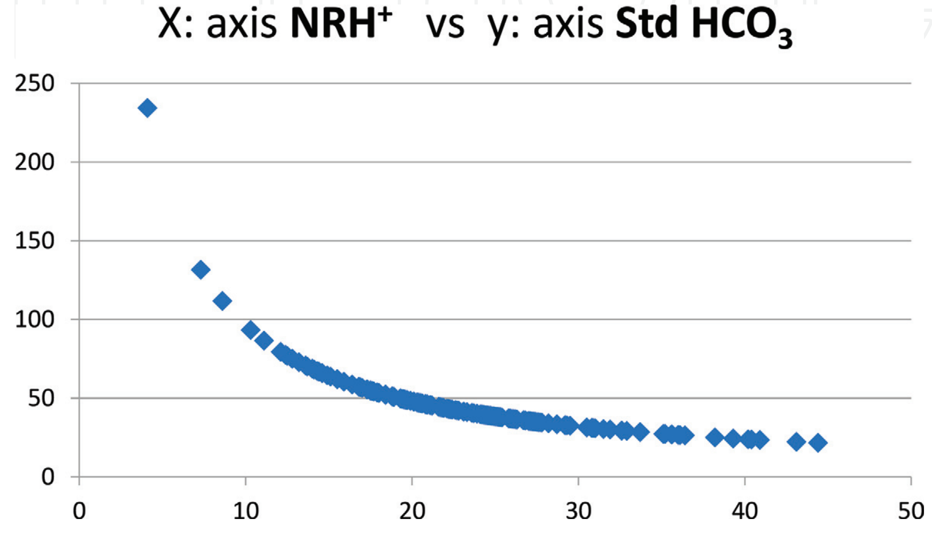

Figure 4.
Relation between NRH^+ *and Std* HCO_3*.*

$NRH^+ = \{24 \times pCO_2\}/\text{Std } HCO_3$
$= \{24 \times 40\}/\text{Std } HCO_3$ (pCO_2 is $40\ mmHg$)
$NRH^+ = 960/Std\ HCO_3$
$NRpH = 9 - \log [NRH^+]$

Calculation of ΔRpH:

$pH = 9 - \log [H^+]$
$NRpH = 9 - \log [NRH^+]$
$pH - NRpH = 9 - \log [H^+] - 9 + \log [NRH^+]$
$= \log [NRH^+/H^+]$ or $-\log [H^+/NRH^+]$
H^+ (hydrogen ion concentration) $= \{24 \times pCO_2\}/HCO_3$
NRH^+ (non-respiratory hydrogen ion concentration)
$= \{24 \times 40\}/\text{Std } HCO_3$
$[NRH^+]/[H^+] = \{24 \times 40\}/\text{Std } HCO_3/\{24 \times pCO_2\}/HCO_3$
$= 40 \times \{(HCO_3/Std\ HCO_3)/pCO_2\}$
Or in terms of carbonic acid [$pCO_2 = H_2CO_3/0.03$], this can be written as
$= 1.2 \times \{(HCO_3/Std\ HCO_3)/H_2CO_3\}$
$\text{pH} - \text{NRpH} = \log [\text{NRH}^+/\text{H}^+]$
$\text{pH} - \text{NRpH} = \log 40 + \log (\text{HCO}_3/\text{Std HCO}_3) - \log(\text{pCO}_2)$
$[pH - NRpH] = 1.6 + \log\{(HCO_3/Std\ HCO_3)/pCO_2\}$

At pCO_2 of *40 mmHg*, *pH − NRpH* is *zero* (because bicarbonate and standard bicarbonate values are equal, log 1 is zero, and log 40 is 1.6). At higher pCO_2 levels (*>40 mmHg*), the value of [*pH − NRpH*] is *negative* which denotes the *acidic influence* of increased pCO_2. At lower pCO_2 levels (*<40 mmHg*), the value of [*pH − NRpH*] is *positive* which denotes the *alkaline influence* of decreased pCO_2:

$[pH - NRpH] = 1.6 + \log \{(HCO_3/Std\ HCO_3)/pCO_2\}$
where NRpH denotes the non-respiratory pH.
$\text{pH} = 9 - \log [\text{H}^+]$
$\text{NRpH} = 9 - \log [\text{NRH}^+]$
$pH - NRpH = 9 - \log [H^+] - 9 + \log [NRH^+]$
$= \log [NRH^+]/[H^+]$ or $-\log [[H^+]/[NRH^+]]$

The *magnitude* and *direction* (positive or negative) of the changes in the parameter *ΔRpH* (pH − NRpH) denote the respiratory influence in causing changes in pH. The value is *negative* for *acidic* effect and *positive* for *alkaline* effect. At pCO_2 of *40 mmHg*, pH − NRpH is *zero* [14].

3.1 Net changes in total pH

The net changes in *total pH* (actual pH) include both the changes in *respiratory* and *non-respiratory* (metabolic) components affecting the pH [14]:

$\Delta\text{pH} = \Delta\text{RpH} + \Delta\text{NRpH}$
$\text{pH} - 7.4 = \Delta\text{RpH} + \text{NRpH} - 7.4$

where ΔNRpH (NRpH − 7.4) denotes the changes in pH due to metabolic component.

3.2 Predicted respiratory pH

$\text{pH} = 7.4 + \Delta\text{RpH} + \Delta\text{NRpH}$
$7.4 + \Delta\text{RpH} - \text{pH} = -\Delta\text{NRpH}$
$Pr\ RpH - pH = -\Delta NRpH\ \{Pr\ RpH\ (\text{predicted respiratory pH}) = 7.4 + \Delta RpH\}$

The predicted respiratory pH is the *pH* at which the *changes in pH* due to *metabolic* component are *zero* (*ΔNRpH is zero)*.

The difference between the *predicted respiratory pH* and *actual pH* denotes the changes in pH due to metabolic component. The *magnitude* and *direction* (positive or negative) of the changes in the parameter *ΔNRpH* (NRpH − 7.4) are due to the accumulation of acids other than carbonic acid or bases. The value is *negative* for *acidic* effect and *positive* for *alkaline* effect. This is one of the postulates of the acid-base balance theory recently published. If the *actual pH* is *less* than the *predicted respiratory pH*, *ΔNRpH* is *negative*. If the *actual pH* is *greater* than the *predicted respiratory pH*, *ΔNRpH* is *positive* [15–18].

NRPH-7.4:

$$
\begin{aligned}
\textit{NRPH-7.4} &= 9 - \log\,[NRH^+] - \{9 - \log\,[40] \\
&= 9 - \log\,[NRH^+] - 9 + \log\,[40] \\
&= \log\,\{[40]/[NRH^+]\} \text{ or } -\log\,\{[NRH^+]/[40]\}
\end{aligned}
$$

<u>*7.4*</u> + <u>*ΔRpH:*</u>

$$
\begin{aligned}
7.4 + \Delta RpH &= \{9 - \log\,[40] + 9 - \log\,[H^+] - 9 + \log\,[NRH^+] \\
&= 9 + \log[NRH^+]/\{[H^+] \times [40]\}
\end{aligned}
$$

$$
\begin{aligned}
\{\Delta RpH\ (pH - NRpH) &= 9 - \log\,[H^+] - 9 + \log\,[NRH^+]\} \\
&= \log\,\{[NRH^+]/[H^+]\} \text{or} -\log\,\{[H^+]/[NRH^+]\}
\end{aligned}
$$

Pr Resp Ph related to $[NRH^+]/\{[H^+] \times [40]\}$

3.3 Net changes in total hydrogen ion concentration

The sum total changes in the hydrogen ion concentration $(\Delta H^+ = [H^+] - [40])$ in the blood include both the changes due to respiratory $(\Delta RH^+ = [H^+] - [NRH^+])$ and non-respiratory (metabolic) components $(\Delta NRH^+ = [NRH^+] - [40])$:

$$
\begin{aligned}
&[\Delta RH^+/H^+] = [H^+ - NRH^+]/[H^+] = 1 - \{[NRH^+]/[H^+]\} \\
&[\Delta NRH^+/40] = (NRH^+ - 40)/40 \text{ or} \\
&-[\Delta NRH^+/40] = (40 - NRH^+)/40 \\
&\qquad = 1 - \{(NRH^+/40)\}.
\end{aligned}
$$

The hydrogen ion concentration is 40 at *pH 7.4* which denotes the *homeostatic set point* of acid-base balance [14, 18].

4. New graphical tool

This new graphical tool developed for ABG interpretation contains four quadrants. In the x-axis, standard base excess values were taken, and in the y-axis, the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 values was taken to analyze the various acid-base disturbances which are clearly shown in the four-quadrant graph (**Figure 3**).

In the *first quadrant* (both x- and y-axes are positive), if the plotted area is toward the x-axis, then it represents metabolic alkalosis, and if the area is toward the y-axis, then it represents respiratory acidosis. The plotted area in between and higher may represent combined acid-base disturbances (metabolic alkalosis and respiratory acidosis). The combined acid-base disturbances may be due to compensatory mechanism or mixed acid-base disorders.

In the *second quadrant* (the x-axis is positive, and the y-axis negative), if the plotted area is toward the y-axis, then it represents respiratory alkalosis, and if the area is in between and lower, then it may represent combined acid-base disturbances (metabolic alkalosis and respiratory alkalosis).

In the *third quadrant* (both x- and y-axes are negative), if the plotted area is toward the x-axis, then it represents metabolic acidosis, and if the area is in between and lower, then it represents both metabolic acidosis and respiratory alkalosis. In the *fourth quadrant* (the x-axis is negative and the y-axis is positive), if the area is toward the y-axis, then it represents respiratory acidosis, and if the area is in between and higher, then it may represent both metabolic acidosis and respiratory acidosis [1].

The *acid-base disorders* can be classified and plotted in the *four-quadrant graph* by using the values of standard base excess and the ratio of (HCO_3 − standard HCO_3)/H_2CO_3. Each acid-base disorder will occupy any of the four quadrants, and the normal ABG analysis reports will be seen around the center of the graph. ABG interpretation is very essential for critically ill patients. Immediate analysis, interpretation, and prompt treatment may reduce the morbidity and mortality of the patients. [1] This newer graphical tool may provide a rough guide and help in easier and quicker interpretation of ABG reports. A minor drawback of this graphical tool is that, as the pCO_2 increases, the *ratio of (HCO_3 − standard HCO_3)/H_2CO_3* also increases and afterward the curve flattens. This may not clearly demarcate the different higher levels of pCO_2 values. Although the ratio of (HCO_3 − standard HCO_3)/H_2CO_3 differentiates the respiratory acidosis and respiratory alkalosis, it may not clearly differentiate the different pCO_2 levels. But this can be *corrected (rectified)* in a three-dimensional graph if pCO_2 values are included in the third axis (z-axis). The parameter *(pCO_2 − 40 mmHg)* should be taken in the third axis, because the ratio (HCO_3 − standard HCO_3)/H_2CO_3 is zero at *pCO_2 of 40 mmHg*, so that the *zero central point* is *common* to all the three parameters of the three axes [18].

Arterial blood gas reports should be interpreted with clinical correlation. This newer graphical tool clearly demonstrates that the different acid-base disorders in a four-quadrant graph method may provide a rough guide to interpret the results quickly and easily. The current research study tries to emphasize the clinical significance of this newer diagnostic tool, which, used along with other ABG parameters and proper clinical correlation, may help in better interpretation of ABG reports.

The concept of non-respiratory hydrogen ion concentration plays a key role in understanding of ABG interpretation, yet often it is not discussed in detail during

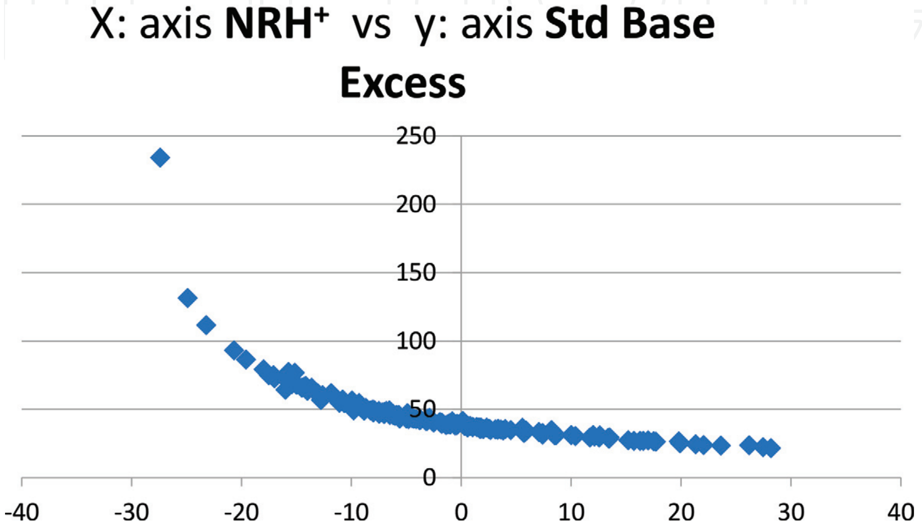

Figure 5.
Relation between NRH^+ and Std base excess.

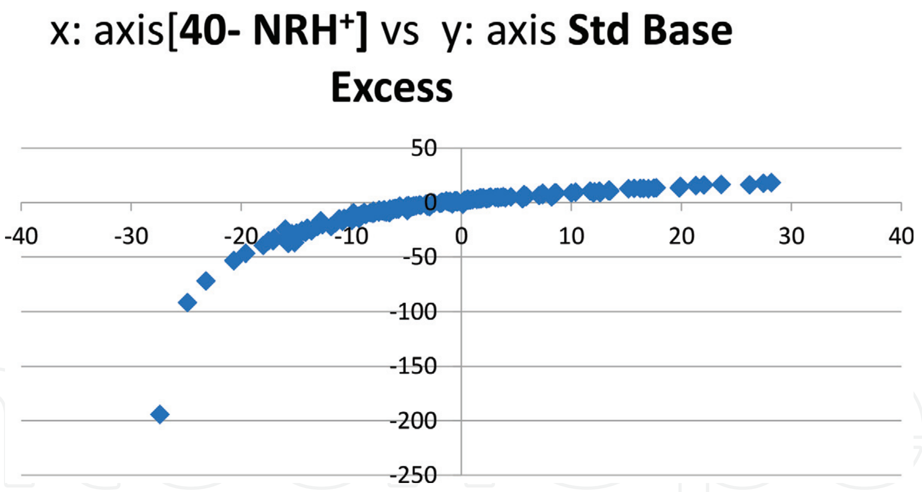

Figure 6.
Relation between [40 − NRH+] and Std base excess.

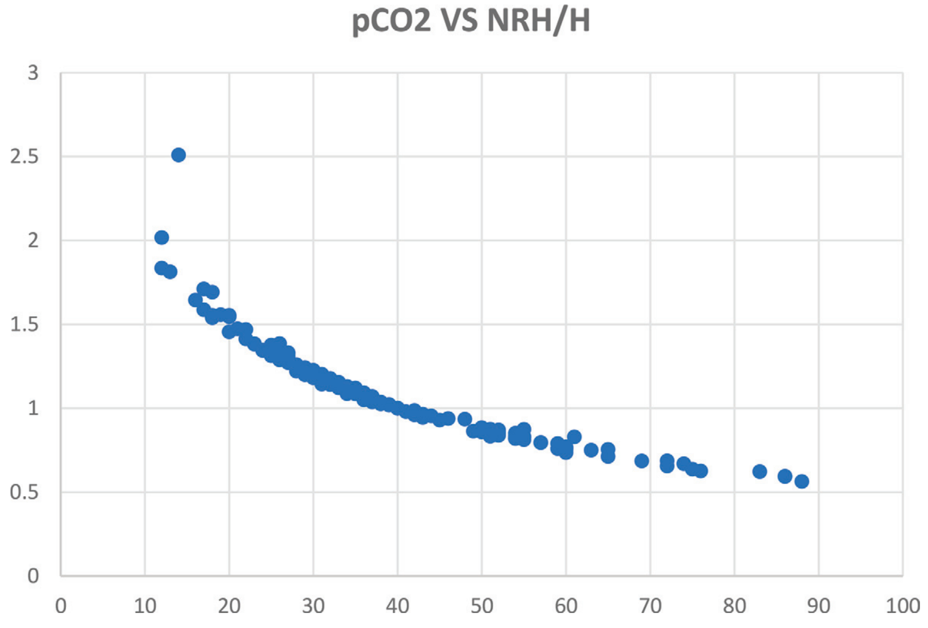

Figure 7.
X-axis pCO_2 vs. y-axis [NRH]/[H].

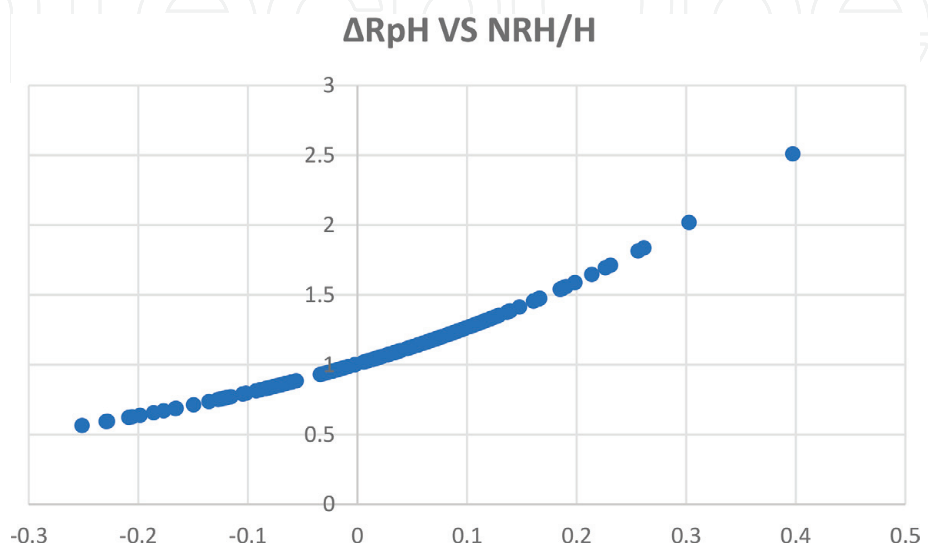

Figure 8.
X-axis ΔRpH vs. y-axis [NRH]/[H].

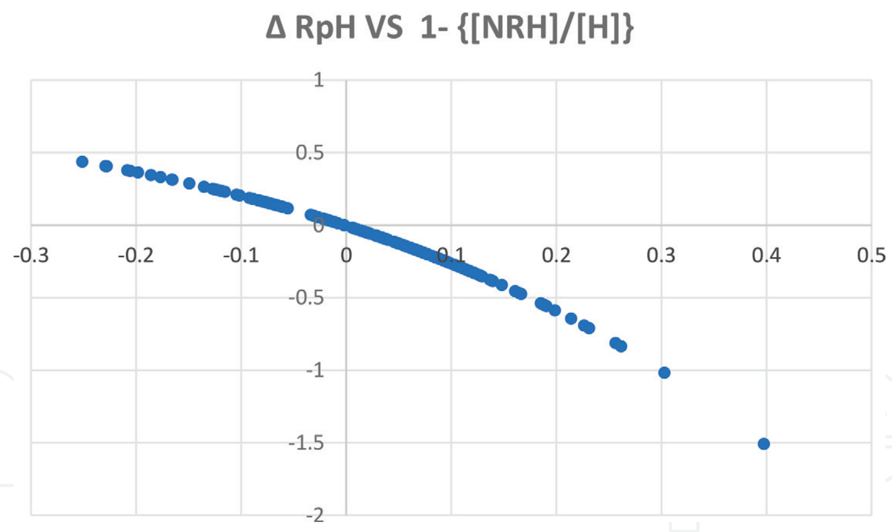

Figure 9.
X-axis ΔRpH vs. y-axis 1 − {[NRH]/[H]}.

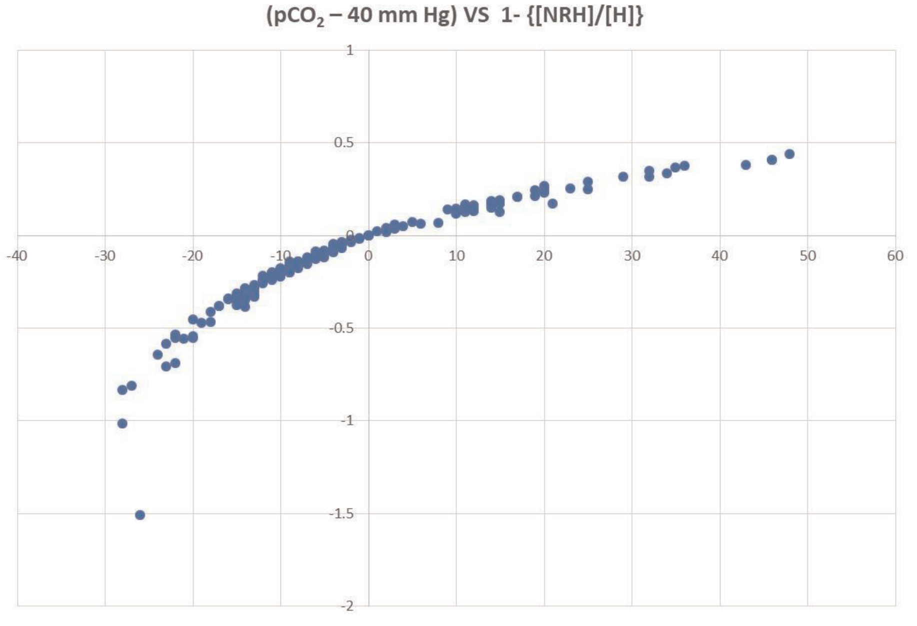

Figure 10.
X-axis (pCO_2 − 40 mmHg) vs. y-axis 1 − {[NRH]/[H]}.

S. no	pH	pCO_2	HCO_3	Std HCO_3	pH-7.4	ΔRpH	ΔNRpH NRPH-7.4	Pr RpH 7.4 + ΔRpH
1.	7.26	31	13.9	15.5	−0.14	0.06	−0.20	7.46
Comment: changes in *net pH (acidic)* are *mainly* due to *metabolic* component, *partly opposed* by *respiratory* component (*alkaline effect*)								
2.	7.5	37	28.9	29.2	0.1	0.03	0.07	7.43
3.	7.48	43	32	30.9	0.08	−0.02	0.10	7.38
Comment: changes in *net pH (alkaline)* are mainly due to *metabolic* component								
4.	7.41	37	23.5	24.3	0.01	0.02	−0.01	7.42
5.	7.39	38	23	23.6	−0.01	0.01	−0.02	7.41
Comment: changes in *net pH* are *normal*								
6.	7.02	61	15.8	12.5	−0.38	−0.08	−0.30	7.32
Comment: changes in *net pH (acidic)* are *mainly* due to *metabolic* component and *partly* due to *respiratory* component								

S. no	pH	pCO_2	HCO_3	Std HCO_3	pH-7.4	ΔRpH	ΔNRpH NRPH-7.4	Pr RpH 7.4 + ΔRpH
7.	7.5	57	44.5	39.3	0.1	−0.10	0.20	7.30
Comment: changes in *net pH (alkaline)* are *mainly* due to *metabolic* component, *partly opposed* by *respiratory* component (*acidic effect*)								
8.	7.4	72	44.6	36.1	0	−0.17	0.17	7.23
Comment: changes in *net pH* are *zero*. The changes in pH due to *metabolic* and *respiratory* component are *equal* and *opposite*. So, they *cancelled out each other* and the net change is zero								
9.	7.17	76	27.7	23.3	−0.23	−0.21	−0.02	7.19
Comment: changes in *net pH (acidic)* are *mainly* due to *respiratory* component								
10.	7.6	12	11.8	19.5	0.2	0.30	−0.10	7.70
Comment: changes in *net pH (alkaline)* are *mainly* due to *respiratory* component, *partly opposed* by *metabolic* component (*acidic effect*)								
11.	7.02	14	3.6	4.1	−0.38	0.40	−0.78	7.80
Comment: changes in *net pH (acidic)* are *mainly* due to *metabolic* component, *partly opposed* by *respiratory* component (*alkaline effect*)								

Table 1.
Examples of ABG data showing metabolic and respiratory components involved in net changes in total pH.

ABG interpretation because it is not routinely applied at the clinical practice due to the lack of simple formulae to calculate the same and nonavailability of its interrelationship with the other acid-base parameters. In the recently published research study, calculation of non-respiratory hydrogen ion concentration from standard bicarbonate and its relationship with other commonly utilized ABG parameters were discussed with the postulates of the acid-base balance theory and shown in **Figures 5–10** and *tabulated* in **Table 1** [14, 18].

5. Predicted respiratory pH

The predicted respiratory pH is usually calculated by pCO_2 variance. This calculation is slightly different for higher (>40 mmHg) and lower (<40 mmHg) pCO_2

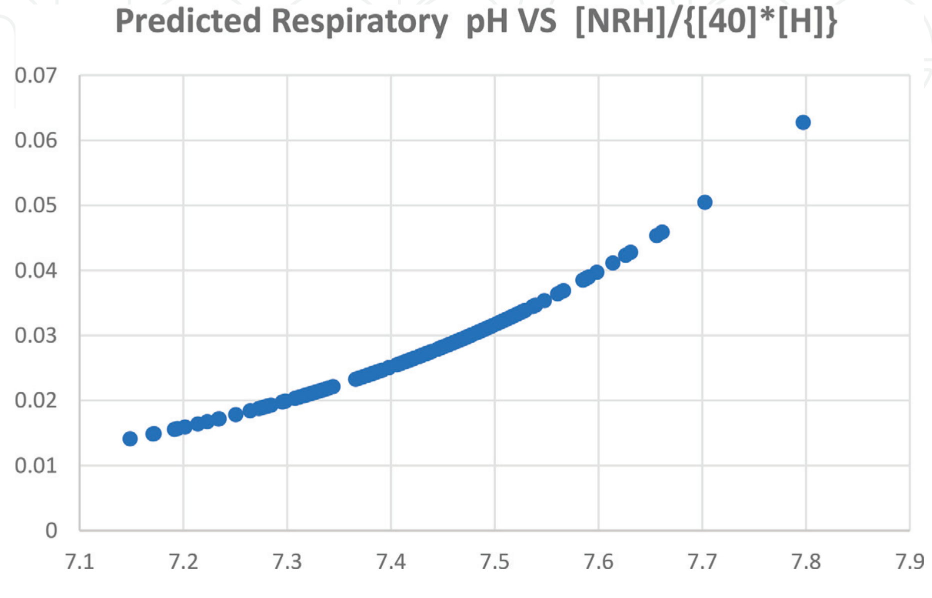

Figure 11.
X-axis predicted respiratory pH vs. y-axis [NRH]/{[40][H]}.*

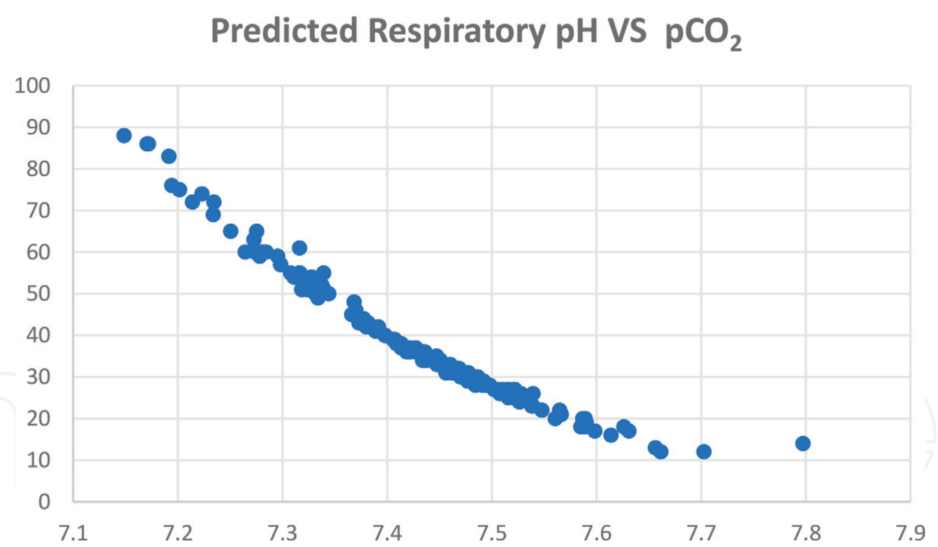

Figure 12.
X-axis predicted respiratory pH vs. y-axis pCO_2.

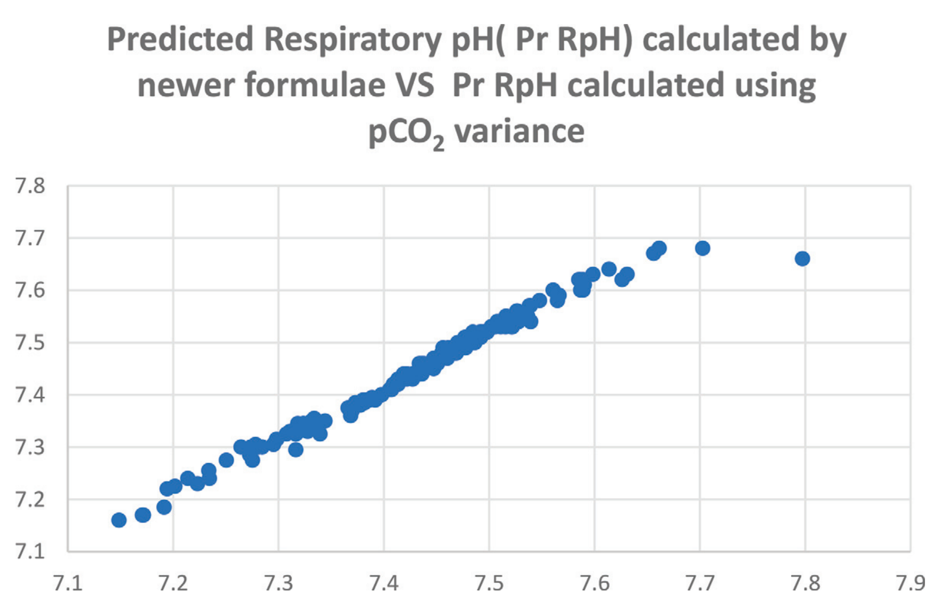

Figure 13.
X-axis predicted respiratory pH(Pr RpH) calculated by newer formulae vs. y-axis Pr RpH calculated using pCO_2 *variance.*

Predicted respiratory pH calculation using pCO_2 variance (previous method)		
Parameter	**pCO_2 > 40 mmHg**	**pCO_2 < 40 mmHg**
pCO_2 variance	$(pCO_2 - 40)/100$	$(40 - pCO_2)/100$
Predicted respiratory pH	$7.4 - (pCO_2 \text{ variance})/2$	$7.4 + (pCO_2 \text{ variance})$
Predicted respiratory pH calculation using newly derived formulae		
	Formulae is the same for all the values of PCO_2	
ΔRpH	$[pH - NRpH] = 1.6 + \log\{(HCO_3/\text{Std } HCO_3)/pCO_2\}$	
Predicted respiratory pH	$7.4 + \Delta RpH$	

Table 2.
Comparison of predicted respiratory pH calculation (one by previous method using pCO_2 *variance and the other by newly derived formulae).*

levels. The difference between the predicted respiratory pH and the measured pH reflects the metabolic pH change. [15] The predicted respiratory pH is calculated by using a newly derived formula which is common for all pCO_2 values [18]. The graphical relationship is shown in **Figures 11–13** and tabulated in **Table 2**.

6. Postulates of the acid-base balance theory

The postulates of the acid-base balance theory are listed below [14]:

1. The net changes in pH of the blood reflect the sum total changes in the hydrogen ion concentration in the blood. The net changes in total or actual pH [ΔpH (pH − 7.4)] are due to both the changes in respiratory [ΔRpH (pH − NRpH)] and non-respiratory (metabolic) components [ΔNRpH (NRpH − 7.4)] affecting the pH.

2. The sum total changes in the hydrogen ion concentration ($\Delta H + = [H^+] - [40]$) in the blood include both the changes due to respiratory ($\Delta RH^+ = [H^+] - [NRH^+]$) and non-respiratory (metabolic) components ($\Delta NRH^+ = [NRH^+] - [40]$).

3. The non-respiratory hydrogen ion concentration $[NRH^+]$ has a unique value for a given standard bicarbonate concentration represented by the relation $NRH^+ = 960/\text{Std bicarbonate}$.

4. The concentration of hydrogen ion excess given by $[NRH^+ - 40]$ is directly proportional to the base deficit. This quantity with opposite sign $[40 - NRH^+]$ is directly proportional to the base excess. Standard base excess is the base excess at hemoglobin concentration of 5 g/dl.

5. The changes in the dependent variable non-respiratory hydrogen ion concentration $[NRH^+]$ representing the non-respiratory (metabolic) component are due to the changes by the independent variables, namely, strong ion difference (SID) and the total concentration of weak nonvolatile acids, namely, albumin and phosphate [ATOT].

6. The changes in the dependent variable $[HCO_3]$ are a marker of metabolic acid-base disturbances and not its causative mechanism.

7. The magnitude and direction (positive or negative) of the changes in the parameter ΔNRpH(NRpH − 7.4) are due to the accumulation of acids other than carbonic acid or bases. The value is negative for acidic effect and positive for alkaline effect.

8. The magnitude and direction (positive or negative) of the changes in the parameter ΔRpH(pH − NRpH) denote the respiratory influence in causing changes in pH represented by the relation $pH - NRpH = 1.6 + \log\{(HCO_3/\text{Std } HCO_3)/pCO_2\}$. The value is negative for acidic effect and positive for alkaline effect.

9. The ratio $[NRH^+/H^+]$ is directly proportional to the parameter ΔRpH (pH − NRpH) which denotes the respiratory influence of pCO_2.

10. The respiratory influence of pCO_2 in changing pH through bicarbonate is a variable one (ratio of HCO_3/Std HCO_3) depending on the acute or chronic conditions or compensations and through carbonic acid is a constant one given by $(H_2CO_3 - 1.2)/H_2CO_3$.

7. Conclusion

Arterial blood gas analysis test is one of the most commonly employed point-of-care testings in intensive care units, yet the understanding of acid-base disturbances and interpretation of ABG reports are sometimes a challenging task especially for critically ill patients with multiorgan failure. The graphical relationship between the metabolic and respiratory components of the net changes in pH and the total changes in hydrogen ion concentration with other ABG parameters like standard base excess, bicarbonate, standard bicarbonate, and pCO_2 will help in better understanding of the arterial blood gas interpretation which results in proper, quicker, and better management of the patient's critical conditions. A newer graphical tool developed using standard base excess and the ratio of $(HCO_3 - \text{standard } HCO_3)/H_2CO_3$ may help in easier and quicker interpretation of ABG reports. This simple four-quadrant graph method may provide a rough guide for ABG interpretation, which, when applied at the appropriate time, results in timely management.

Although, standard bicarbonate value is not routinely utilized for ABG interpretation, the parameters derived from standard bicarbonate plays a vital role in the understanding of acid-base disturbances. The application of these newly derived parameters and the four-quadrant graphical tool may serve as a supporting tool for teaching and diagnostic purposes, which when properly correlated with clinical conditions and other ABG parameters results in better understanding and quicker interpretation of ABG reports.

Conflict of interest

Nil.

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