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Biochemistry Section

Application of Compensation Rules in the Four-quadrant Graphical Tool for Arterial Blood Gas Interpretation: A Cross-sectional Study

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ABSTRACT

Introduction: Arterial Blood Gas (ABG) interpretation plays an indispensable role in emergency medicine and the care of intensive care patients, yet it remains a challenging task. Although several graphical methods exist for ABG interpretation, they are not commonly used at the bedside. The existing graphs are complicated, difficult to understand, and unable to diagnose many disorders. In previous research articles, the current author developed and published a four-quadrant graphical tool for ABG interpretation. The tool incorporates compensation rules, which are crucial for identifying changes resulting from compensations or the presence of a second primary acid-base disorder.

Aim: To develop a method for applying compensation rules in a four-quadrant graphical tool to interpret ABG reports for complex acid-base disorders in clinical practice.

Materials and Methods: This cross-sectional study was conducted at Shri Sathya Sai Medical College and Research Institute, Chennai, Tamil Nadu, India, from November 2022 to April 2023. A total of 232 ABG samples were utilised, and the values of pH, pCO_2, HCO_3, Standard HCO_3, and Standard Base Excess (SBE) were recorded. These values were classified according to different acid-base disorders. Three derived ratios were calculated using the values of pCO_2, bicarbonate, and standard bicarbonate, as these ratios change in various acid-base disorders and provide clues for differentiating between different acid-base disturbances. A four-quadrant graph method was constructed using the values of SBE, pCO_2, and these ratios. Subsequently, compensation rules were applied to this graph method.

Results: The four-quadrant method facilitated the easy identification of different acid-base disorders, and the application of compensation rules further simplified the identification of mixed or compensatory acid-base disorders.

Conclusion: The application of compensation rules in this four-quadrant graphical tool for ABG interpretation distinguishes this tool as a unique method among existing approaches. This tool offers an optimal and simplified approach for interpreting ABG results for complex acid-base disturbances, making it highly suitable for clinical practice at the bedside.

Keywords: Acid-base disturbances, Graphical interpretation, Mixed disorder

INTRODUCTION

ABG interpretation plays an indispensable role in emergency medicine and the care of intensive care patients, yet its interpretation is challenging. Only a few graphical methods exist for ABG interpretation, such as the Siggaard-Andersen chart (S-A chart), Davenport or Bicarbonate-pH diagram, and Grogono diagram. However, these methods are not commonly utilised in clinical practice. The S-A chart has some flaws in diagnosing acid-base disorders with various combinations of pH-pCO_2 values. The Davenport or Bicarbonate-pH diagram is complicated and difficult to understand. The Grogono diagram, a two-axis diagram using pCO_2 on the horizontal axis and SBE on the vertical axis, is considered superior to the S-A chart but fails to provide accurate interpretation in atleast 25% of cases [1-5]. Therefore, a newer graphical method utilising the four-quadrant approach was developed by the current author and published in previous research articles [6,7].

Bicarbonate is calculated using the Modified Henderson equation. Standard bicarbonate represents the concentration of bicarbonate in the plasma from blood equilibrated with a normal $PaCO_2$ (40 mmHg) and a normal pO_2 (over 100 mmHg) at a normal temperature (37°C). Under normal ventilation, the actual bicarbonate and standard bicarbonate concentrations are approximately equal. However, in abnormal respiration (either hypoventilation or hyperventilation), the two values change and deviate from each other based on variations in pCO_2 concentration [6,8,9].

Simple acid-base disorders are relatively easy to interpret, but in clinical practice, most ABG results are complex, involving compensations or mixed disorders, which are challenging to understand and interpret [3,6]. Compensation rules play a significant role in identifying changes resulting from compensations or the presence of a second primary acid-base disorder. The aim of the current study was to apply the developed concept of compensation rules in this four-quadrant graphical tool for ABG interpretation.

MATERIALS AND METHODS

This cross-sectional study was conducted from November 2022 to April 2023 at Shri Sathya Sai Medical College and Research Institute, Chennai, Tamil Nadu, India. Ethical clearance was obtained (IEC No: 2016/272), and this study serves as an extension of author's previous research [6-8]. A total of 232 ABG samples were collected from ICU patients for analysis. The consistency of the ABG reports was assessed using the Modified Henderson Equation, and consistent results were included while inconsistent results were excluded [3,6]. At a pCO_2 of 40 mmHg, the H_2CO_3 concentration is 1.2 mmol/L (H_2CO_3=0.03×pCO_2). The calculation of SBE and the novel-derived ratios are detailed below [6,7,10].

Standard Base Excess (SBE)=$cHCO_3$-24.8+16.2×(pH-7.40)

Ratio 1=HCO_3/Std HCO_3

Ratio 2=(HCO_3/H_2CO_3)- (Std HCO_3/H_2CO_3) OR

Ratio 2=(HCO_3-Std HCO_3)/H_2CO_3

Modified Ratio 2=(Std HCO_3/1.2)-(HCO_3/H_2CO_3)

Modified Ratio 2 (modified version of Ratio 2) was used as it is logical to correlate Std bicarbonate with an H_2CO_3 concentration of 1.2 mmol/L.

Compensation bedside rules: The Boston Method (6 rules) using bicarbonate or the Copenhagen Method (4 rules) using SBE can be applied to assess compensation, but the six bicarbonate-based bedside rules are more commonly utilised in clinical practice [11-13].

Six bicarbonate-based bedside rules:

Rule for acute respiratory acidosis:

Expected (HCO_3)=24+{(Actual pCO_2-40)/10}

Rule for chronic respiratory acidosis:

Expected (HCO_3)=24+4 {(Actual pCO_2-40)/10}

Rule for acute respiratory alkalosis:

Expected (HCO_3)=24-2 {(40-Actual pCO_2)/10}

Rule for chronic respiratory alkalosis:

Expected (HCO_3)=24-5 {(40-Actual pCO_2)/10} (range:±2)

Rule for a metabolic acidosis:

Expected pCO_2=1.5×(HCO_3)+8 (range: ±2)

Rule for a metabolic alkalosis:

Expected pCO_2=0.7×(HCO_3)+20 (range: ±5)

Four SBE-based bedside rules:

Acute respiratory acidosis or alkalosis:

An acute deviation in pCO_2 will not alter the SBE. If SBE changes then it denotes metabolic disturbances only [11-13].

Chronic respiratory acidosis or alkalosis:

SBE=0.4×(pCO_2-40)

Metabolic acidosis:

Expected CO_2=40+SBE

Metabolic alkalosis:

Expected CO_2=40+(0.6×SBE)

STATISTICAL ANALYSIS

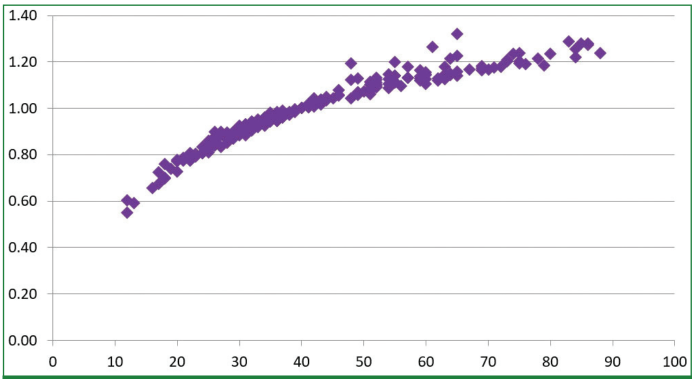
These graphs were constructed using scatter plots with two variables in MS Excel 2019 version.

RESULTS

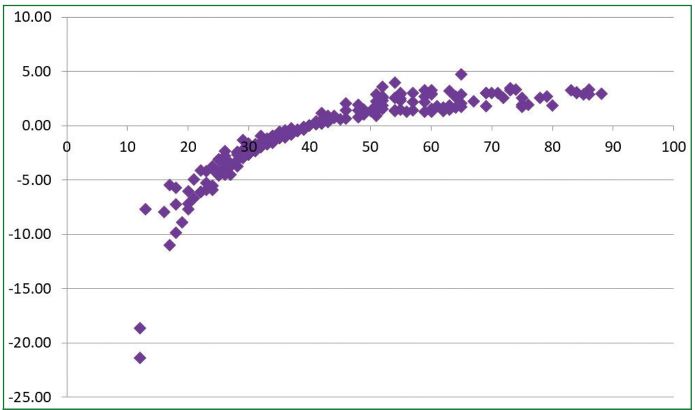
The total of 232 samples was classified into various acid-base disorders and is clearly depicted in [Table/Fig-1]. The graphical relationship between pCO_2 and ratio 1, ratio 2, and modified ratio 2 is clearly depicted in [Table/Fig-2-4], respectively.

Classification of acid base disorders into different groups	
Group-I Normal: 25 cases **Group-II Respiratory Acidosis: 32** RA 1: (HCO_3 22 to 26 mmol/L)-10 RA 2: (HCO_3 >26 ≤30 mmol/L)-6 RA 3: (HCO_3 >30 ≤40 mmol/L)-13 RA 4: (HCO_3 >40 mmol/L)-3 **Group-III Respiratory Alkalosis: 53** R Alk 1: (HCO_3 ≤10 mmol/L)-1 R Alk 2: (HCO_3 >10 ≤15 mmol/L)-4 R Alk 3: (HCO_3 >15 ≤18 mmol/L)-9 R Alk 4: (HCO_3 >18 <22 mmol/L)-16 R Alk 5: (HCO_3 22 to 26 mmol/L)-23	**Group-IV Metabolic Acidosis: 47 cases** Met Ac 1: pCO_2 ≤15 mm of Hg-1 Met Ac 2: pCO_2 16 to 20 mm of Hg-5 Met Ac 3: pCO_2 21 to 25 mm of Hg-8 Met Ac 4: pCO_2 26 to 30 mm of Hg-10 Met Ac 5: pCO_2 31 to 34 mm of Hg-7 Met Ac 6: pCO_2 35 to 40 mm of Hg-12 Met Ac 7: pCO_2 41 to 45 mm of Hg-4 **Group-V Metabolic Alkalosis: 34 cases** Met Alk 1: pCO_2 35 to 40 mm of Hg-8 Met Alk 2: pCO_2 41 to 45 mm of Hg-4 Met Alk 3: pCO_2 46 to 50 mm of Hg-3 Met Alk 4: pCO_2 51 to 55 mm of Hg-12 Met Alk 5: pCO_2 ≥56 mm of Hg-7
Group-VI Miscellaneous Groups: 41 Mis 1 (↓ pH, ↑ pCO_2 & ↓ HCO_3): 11 Mis 2 (Normal pH, ↑ pCO_2 & ↑ HCO_3): 16 Mis 3 (Normal pH, ↓ pCO_2 & ↓ HCO_3): 14	**Total number of cases in all the groups: 232**

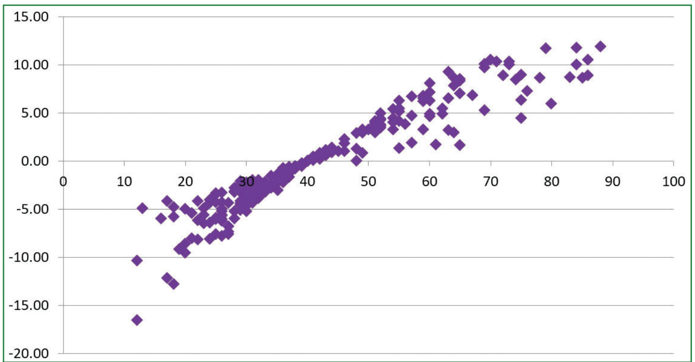
[Table/Fig-1]: Classification of acid base disorders into different groups.



[Table/Fig-2]: pCO_2 VS ratio 1.

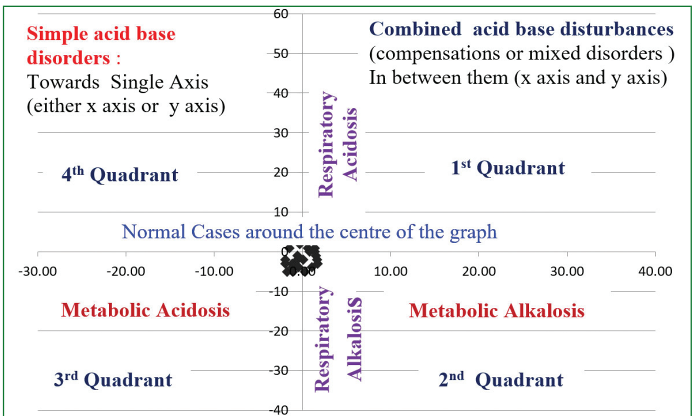


[Table/Fig-3]: pCO_2 VS ratio 2.

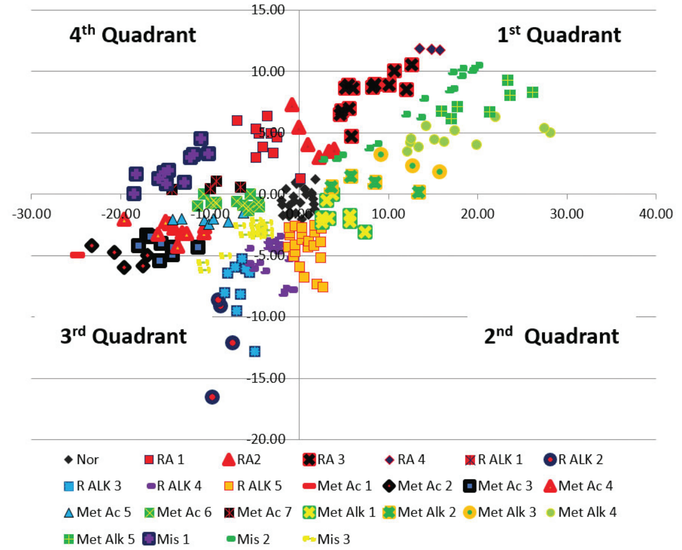


[Table/Fig-4]: pCO_2 VS modified ratio 2.

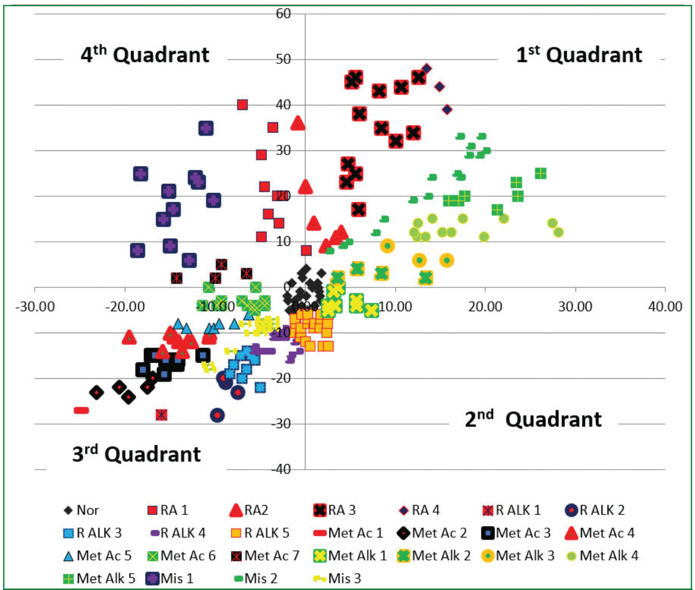
A sample model of a four-quadrant graph using SBE and (pCO_2-40 mmHg) parameters is shown in [Table/Fig-5], clearly illustrating the different areas of various acid-base disturbances. In [Table/Fig-6], a four-quadrant graph was constructed using SBE and modified ratio 2 for all the 232 cases. Similarly, in [Table/Fig-7], a four-quadrant graph was constructed using SBE and (pCO_2-40 mmHg) for all the 232 cases. The application of compensation rules in the four-quadrant graph method, using the concept of a shift in the plotted point's position, is demonstrated in [Table/Fig-8].



[Table/Fig-5]: Model of 4 quadrant graph using SBE and (pCO_2-40).



[Table/Fig-6]: Graphical Tool X axis: Std. BE VS Y axis: Modified Ratio 2.



[Table/Fig-7]: Graphical Tool X axis: Std BE VS Y axis: pCO_2 - 40.

Parameter to assess compensations	Changes in direction	Shift	Acid base disorder
pCO_2 - EXP pCO_2	Greater positive	Upward positive shift	Respiratory acidosis
pCO_2 - EXP pCO_2	Greater negative	Downward negative shift	Respiratory alkalosis
pCO_2 - EXP pCO_2	Within certain acceptable limits	No shift: only compensation	No second acid base disorder
(HCO_3-) - EXP (HCO_3-)	Greater positive	Right positive shift	Metabolic alkalosis
(HCO_3-) - EXP (HCO_3-)	Greater negative	Left negative shift	Metabolic acidosis
(HCO_3-) - EXP (HCO_3-)	Within certain Acceptable limits	No shift: Only compensation	No second acid base disorder

[Table/Fig-8]: Application of compensation rules and identification of acid base disorders using the SHIFT.

DISCUSSION

The actual bicarbonate and standard bicarbonate concentrations are approximately equal under normal ventilation. However, in hypoventilation and hyperventilation, these two values deviate from each other. At a pCO_2 of 40 mmHg, both bicarbonate and standard bicarbonate values are equal, resulting in a difference of zero. The ratio 2 value is zero when the ratio 1 value is one. The ratio 1 (HCO_3/Std HCO_3) is greater than 1 for increased pCO_2 and less than 1 for decreased pCO_2. The ratio 2 is positive and greater for increased pCO_2, and negative and greater for decreased pCO_2 values [6,7,14].

Respiratory acid-base disorders and compensations in metabolic acid-base disorders due to respiratory mechanism changes affect the values of these ratios in different conditions. These derived ratios provide clues for differentiating various acid-base disturbances [6,7,14]. Modified ratio 2 clearly distinguishes different pCO_2 values. Both ratio 2 and modified ratio 2 are positive and greater for increased pCO_2, and negative and greater for decreased pCO_2 values. Modified ratio 2 is used because Std bicarbonate is measured at a pCO_2 of 40 mmHg, and it seems logical to correlate Std bicarbonate with an H_2CO_3 concentration of 1.2 mmol/L (at a pCO_2 of 40 mmHg).

SBE greater than +2 mmol/L indicates metabolic alkalosis, while SBE less than -2 mmol/L indicates metabolic acidosis. The normal range for pCO_2 is 35 to 45 mmHg. Higher pCO_2 values are observed in respiratory acidosis, while lower pCO_2 values are seen in respiratory alkalosis [6,7,14]. Modified ratio 2 is positive and greater for respiratory acidosis, and negative and greater for respiratory alkalosis.

A four-quadrant graph is constructed for ABG interpretation using SBE and modified ratio 2 values for all 232 cases. Another four-quadrant graph was constructed using SBE and the parameter (pCO_2-40 mmHg). The modified ratio 2 is zero at a pCO_2 of 40 mmHg, so the zero central point is common to all three parameters. A three-dimensional graph can be created by merging these two four-quadrant graphs since SBE is common to both of them on the x-axis [6,7,14].

The various acid-base disorders can be easily visualised in different regions of the four-quadrant graph, with normal levels occupying the central region. In the 1st quadrant (both the x and y axes are positive), metabolic alkalosis and respiratory acidosis are represented. In the 2nd quadrant (x-axis positive and y-axis negative value), metabolic alkalosis and respiratory alkalosis are represented. In the 3rd quadrant (both the x and y axes are negative), metabolic acidosis and respiratory alkalosis are represented. In the 4th quadrant (x-axis negative and y-axis positive), metabolic acidosis and respiratory acidosis are represented [6,7,14].

After identifying the primary disorder of the acid-base disturbances, compensation rules are applied to help identify the presence of compensations or a mixed acid-base disorder. If the measured pCO_2 is higher than the expected pCO_2, it indicates the presence of respiratory acidosis, and if it is lower, it indicates the presence of respiratory alkalosis. If the measured (HCO_3-) value is higher than the expected (HCO_3-), it denotes the presence of metabolic alkalosis, and if it is lower, it denotes the presence of metabolic acidosis. The difference between the measured and the expected level {either pCO_2 or (HCO_3-)} indicates the magnitude of the severity. These steps are routinely performed in ABG interpretation, but it can be an arduous task [11,12,15,16].

These concepts are applied in the graphical tool to facilitate easier interpretation and overcome the challenges of the task. After applying the compensation rules in the four-quadrant graph method, if no major shift (within acceptable limits) is observed in the plotted point's position, it indicates only compensations without the presence of a second acid-base disorder. The combined acid-base disturbances resulting from compensations or mixed acid-base disorders can be easily identified and located using the concept of a shift in the plotted point's position on the four-quadrant graph. An upward positive shift signifies respiratory acidosis, a downward negative shift indicates respiratory alkalosis, a right positive shift represents metabolic alkalosis, and a left negative shift signifies metabolic acidosis. The compensation rules that are commonly used with bicarbonate can also be applied here because the SBE parameter plotted on the

X-axis is calculated using bicarbonate values. Therefore, changes in expected bicarbonate values will be reflected when SBE values are calculated using the expected bicarbonate value. Hence, there is no compulsion to use the compensation rules solely based on SBE.

Limitation(s)

The calculation of the anion gap and delta gap, which helps in identifying hidden metabolic acid-base disorders, cannot be displayed in the graphical tool. This limitation exists in the study; however, it can be calculated separately and correlated with the clinical history.

CONCLUSION(S)

The interpretation of ABG results holds significant clinical value; however, understanding complex acid-base disorders can be challenging. Few graphical methods are available, but they are not practically convenient for clinical practice. The proposed application of compensation rules using the shift concept in the four-quadrant graph method appears to be simpler and easier, addressing the difficulties associated with complex acid-base disorders involving various compensations and mixed disorders. The inclusion of modified ratio two, standard bicarbonate, and compensation rules in this graph method makes it a unique diagnostic tool compared to other existing methods. The incorporation of these parameters, along with the simplified approach of the four-quadrant graph, may make this diagnostic graphical tool a suitable for ABG interpretation, especially for junior staff. However, further confirmation by other researchers working with intensive care unit patients is required for widespread acceptance and adoption of this graphical tool in clinical practice. When used in conjunction with other ABG parameters and proper clinical correlation, this diagnostic ABG tool may aid in better understanding and interpretation of ABG reports, particularly for junior doctors and staff nurses.

REFERENCES

[1] Barnette L, Kautz DD. Creative ways to teach arterial blood gas interpretation. Dimens Crit Care Nurs. 2013;32(2):84-87.

[2] Doig AK, Albert RW, Syroid ND, Moon S, Agutter JA. Graphical arterial blood gas visualization tool supports rapid and accurate data interpretation. Comput Inform Nurs. 2011;29(4 Suppl):TC53-60.

[3] Sood P, Paul G, Puri S. Interpretation of arterial blood gas. Indian J Crit Care Med. 2010;14(2):57-64.

[4] Behrakis P, Vasileiou M, Anastasios L, Nikolaos T. Latest developments in graphic diagnostic approach of arterial blood gases disturbances. Pneumon. 2004;17(2):150-58.

[5] Theakos N, Loukos A, Vassiliou M, Moukas M, Zaka M, Behrakis PK. pH-log$PaCO_2$ diagram for the diagnostic approach of simple acid-base disorders. 2nd Mediterranean Congress on Thoracic Diseases Athens, Greece 4-7 March 1998.

[6] Samuel R. A graphical tool for arterial blood gas interpretation using standard bicarbonate and base excess. Indian J Med Biochem. 2018;22(1):85-89.

[7] Samuel R. Revised graphical tool for ABG interpretation using modified bicarbonate/standard bicarbonate ratio. Int J Clin Chem Lab Med. 2019;5(3):19-29.

[8] Samuel R. Application of standard bicarbonate/carbonic acid ratio in arterial blood gas analysis. Int J Clin Biochem Res. 2018;(2):314-20.

[9] Jørgensen K, Astrup P. Standard bicarbonate, its clinical significance, and a new method for its determination. Scand J Clin Lab Invest. 1957;9(2):122-32.

[10] Rajini Samuel T, Vyshnavi R, Vanaja R, Ragashree CM, Rajagopalan B. Graphical analysis of arterial blood gas analysis using standard base excess. Int J Pharm Sci Rev Res. 2017;46(1):223-28.

[11] Joynt GM, Choi GYS. Chapter: Blood gas analysis in the critically ill Oxford Textbook of Critical Care (2 ed.) Publisher: Oxford University Press, 2016. Doi: 10.1093/med/9780199600830.003.0072.

[12] Kerry Brandis.Chapter: Assessment of Acid-Base Disorders. Acid-base physiology. Open Education Resource LibreTexts Project (https://LibreTexts.org),2023.

[13] Schlichtig R, Grogono AW, Severinghaus JW. Human PaCO2 and standard base excess compensation for acid-base imbalance. Crit Care Med. 1998;26(7):1173-79. Doi: 10.1097/00003246-199807000-00015.

[14] Rajini Samuel T. Who is balancing: Is it RBC or acid-base status? Intech Open Publisher. 2019:01-15. Doi: http://dx.doi.org/10.5772/intechopen.84768.

[15] Bruno CM, Valenti M. Acid-base disorders in patients with chronic obstructive pulmonary disease: A pathophysiological review. J Biomed Biotechnol. 2012;2012:915150.

[16] Oosthuizen NM. Approach to acid-base disorders- A clinical chemistry perspective. CME. 2012;30(7):230-34.

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