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 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-pCO₂ values. The Davenport or Bicarbonate-pH diagram is complicated and difficult to understand. The Grogono diagram, a two-axis diagram using pCO₂ 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 at least 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].

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, pCO₂, HCO₃⁻, Standard HCO₃⁻ 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 pCO₂, 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, pCO₂, 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.

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-pCO₂ values. The Davenport or Bicarbonate-pH diagram is complicated and difficult to understand. The Grogono diagram, a two-axis diagram using pCO₂ 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 at least 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 PaCO₂ (40 mmHg) and a normal pO₂ (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 pCO₂ 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 confirmed with previous research [6-8]. A total of 232 ABG samples were collected from ICU patients for analysis. The consistency of the ABG reports was confirmed with previous research [6-8].

Keywords: Acid-base disturbances, Graphical interpretation, Mixed disorder
Modified Ratio 2 = (Std HCO₃⁻/1.2) – (HCO₃⁻/H₂CO₃)

Modified Ratio 2 (modified version of Ratio 2) was used as it is logical to correlate Std bicarbonate with an H₂CO₃ 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 pCO₂ = 40 + (0.6 × SBE)

**Rule for chronic respiratory acidosis:**
Expected pCO₂ = 40 + SBE

**Rule for chronic respiratory alkalosis:**
Expected pCO₂ = 24 + SBE

**Rule for acute respiratory alkalosis:**
Expected pCO₂ = 1.5 x HCO₃⁻ + 8 (range: ±2)

**Rule for a metabolic acidosis:**
Expected pCO₂ = 0.7 x HCO₃⁻ + 20 (range: ±5)

**Four SBE-based bedside rules:**

**Acute respiratory acidosis or alkalosis:**
An acute deviation in pCO₂ will not alter the SBE. If SBE changes then it denotes metabolic disturbances only [11-13].

**Chronic respiratory acidosis or alkalosis:**
SBE = 0.4 x (pCO₂ - 40)

**Metabolic acidosis:**
Expected CO₂ = 40 + SBE

**Metabolic alkalosis:**
Expected CO₂ = 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 pCO₂ 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**

<table>
<thead>
<tr>
<th>Group-I Normal: 25 cases</th>
<th>Group-IV Metabolic Acidosis: 47 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group-II Respiratory Acidosis: 32</td>
<td>Met Ac 1: pCO₂ ≤15 mm of Hg-1</td>
</tr>
<tr>
<td>RA 1: (HCO₂, 22 to 26 mmol/L)-10</td>
<td>Met Ac 2: pCO₂ 16 to 20 mm of Hg-5</td>
</tr>
<tr>
<td>RA 2: (HCO₂, &gt;26 ≤30 mmol/L)-6</td>
<td>Met Ac 3: pCO₂ 21 to 25 mm of Hg-8</td>
</tr>
<tr>
<td>RA 3: (HCO₂, &gt;30 ≤40 mmol/L)-13</td>
<td>Met Ac 4: pCO₂ 26 to 30 mm of Hg-10</td>
</tr>
<tr>
<td>RA 4: (HCO₂, &gt;40 ≤50 mmol/L)-3</td>
<td>Met Ac 5: pCO₂ 31 to 34 mm of Hg-7</td>
</tr>
<tr>
<td>Group-III Respiratory Alkalosis: 53</td>
<td>Met Ac 6: pCO₂ 35 to 40 mm of Hg-12</td>
</tr>
<tr>
<td>RA 1k: (HCO₂, ≤10 mmol/L)-1</td>
<td>Met Ac 7: pCO₂ 41 to 45 mm of Hg-4</td>
</tr>
<tr>
<td>RA 2k: (HCO₂, &gt;10 ≤15 mmol/L)-4</td>
<td>Group-V Metabolic Alkalosis: 34 cases</td>
</tr>
<tr>
<td>RA 3k: (HCO₂, &gt;15 ≤20 mmol/L)-9</td>
<td>Met Vl: pCO₂ 35 to 40 mm of Hg-8</td>
</tr>
<tr>
<td>RA 4k: (HCO₂, &gt;22 ≤26 mmol/L)-16</td>
<td>Met V2: pCO₂ 41 to 45 mm of Hg-4</td>
</tr>
<tr>
<td>RA 5k: (HCO₂, &gt;26 ≤30 mmol/L)-23</td>
<td>Met V3: pCO₂ 46 to 50 mm of Hg-3</td>
</tr>
<tr>
<td>Group-VI Miscellaneous Groups: 41</td>
<td>Met V4: pCO₂ 51 to 55 mm of Hg-12</td>
</tr>
<tr>
<td>Mis 1 (pH, pCO₂, &amp; HCO₂): 11</td>
<td>Met V5: pCO₂ ≥56 mm of Hg-7</td>
</tr>
<tr>
<td>Mis 2 (Normal pH, pCO₂, &amp; HCO₂): 16</td>
<td>Total number of cases in all the groups: 232</td>
</tr>
<tr>
<td>Mis 3 (Normal pH, pCO₂, &amp; HCO₂): 14</td>
<td></td>
</tr>
</tbody>
</table>

A sample model of a four-quadrant graph using SBE and (pCO₂ - 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 (pCO₂ - 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].
The actual bicarbonate and standard bicarbonate concentrations are approximately equal under normal ventilation. However, in hypventilation 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$_2$CO$_3$ 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 acidosis 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 [6,7,14].

**DISCUSSION**

[Table/Fig-6]: Application of compensation rules and identification of acid base disorders using the SHIFT.

<table>
<thead>
<tr>
<th>Parameter to assess</th>
<th>Changes in direction</th>
<th>Shift</th>
<th>Acid base disorder</th>
</tr>
</thead>
<tbody>
<tr>
<td>pCO$_2$ - EXP pCO$_2$</td>
<td>Greater positive</td>
<td>Upward positive shift</td>
<td>Respiratory acidosis</td>
</tr>
<tr>
<td>pCO$_2$ - EXP pCO$_2$</td>
<td>Greater negative</td>
<td>Downward negative shift</td>
<td>Respiratory alkalosis</td>
</tr>
<tr>
<td>pCO$_2$ - EXP pCO$_2$</td>
<td>Within certain acceptable limits</td>
<td>No shift; only compensation</td>
<td>No second acid base disorder</td>
</tr>
<tr>
<td>(HCO$_3$-) - EXP (HCO$_3$-)</td>
<td>Greater positive</td>
<td>Right positive shift</td>
<td>Metabolic alkalosis</td>
</tr>
<tr>
<td>(HCO$_3$-) - EXP (HCO$_3$-)</td>
<td>Greater negative</td>
<td>Left negative shift</td>
<td>Metabolic acidosis</td>
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<td>Within certain acceptable limits</td>
<td>No shift; only compensation</td>
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</tr>
</tbody>
</table>

[Table/Fig-7]: Graphical Tool X axis: Std BE VS Y axis: pCO$_2$ - 40.

[Table/Fig-8]: Graphical Tool X axis: Std BE VS Y axis: Modified Ratio 2.
Understanding and interpretation of ABG reports, particularly for proper clinical correlation, this diagnostic ABG tool may aid in better practice. When used in conjunction with other ABG parameters and researchers working with intensive care unit patients is required for especially for junior staff. However, further confirmation by other along with the simplified approach of the four-quadrant graph, may to other existing methods. The incorporation of these parameters, in this graph method makes it a unique diagnostic tool compared modified ratio two, standard bicarbonate, and compensation rules various compensations and mixed disorders. The inclusion of difficulties associated with complex acid-base disorders involving graph method appears to be simpler and easier, addressing the practically convenient for clinical practice. The proposed application challenging. Few graphical methods are available, but they are not conveniently 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.

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 conveniently 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