Secondary Responses to Altered Acid-Base Status: The Rules of Engagement

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The physiologic approach to acid-base disorders views blood pH as determined by the prevailing levels of carbonic acid (PaCO₂, the respiratory component) and plasma bicarbonate concentration ([HCO₃⁻], the metabolic component), as stipulated by the Henderson equation, [H⁺] = 24 × PaCO₂/[HCO₃⁻].¹ The four canonical acid-base disorders include the respiratory disorders (acidosis and alkalosis) and the metabolic disorders (acidosis and alkalosis). Whereas the respiratory disorders are expressed as primary changes in PaCO₂, the metabolic disorders are expressed as primary changes in plasma [HCO₃⁻].²,³

Each primary change in either the respiratory or the metabolic component elicits in vivo a secondary response in the countervailing component that is directional and proportional to the primary change, albeit fractionally smaller, thus tending to minimize the change in body acidity. These secondary responses originate from physicochemical buffering and change in ventilation, organic-acid metabolism, and renal acidification. They have been quantified in dogs and humans, are consistent in presence and predictable in magnitude, and are viewed as an integral part of each canonical disorder. Absence of an appropriate secondary response denotes the coexistence of an additional acid-base disorder. Here we address the expected magnitude of the secondary response to each cardinal acid-base disorder in humans and offer caveats for judging the appropriateness of each secondary response.


MAGNITUDE AND TIME COURSE OF THE SECONDARY RESPONSES

Here we examine the mean slope of the secondary response to each cardinal acid-base disorder (Table 1) and the time interval required for each secondary response to reach completion. Toward this end, we reviewed all available human

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Respiratory alkalosis

- Hypercapnia acidifies body fluids and stimulates nonbicarbonate buffers, yielding a small increase in plasma [HCO₃⁻]. This secondary hyperbicarbonatemic response is completed within 5 to 10 minutes and remains stable for several hours. Observations in unanesthetized normal humans studied in an environmental chamber (inspired CO₂ 7 and 10%) reveal a mean Δ[HCO₃⁻]/ΔPaCO₂ slope of 0.1 mEq/L per mmHg; expected [HCO₃⁻] = 24 + ([current PaCO₂ - 40] × 0.1). An essentially identical slope is obtained in humans in whom respiratory acidosis is induced by endogenous hypercapnia. Sustained hypercapnia causes an additional, larger increase in plasma [HCO₃⁻] owing to stimulation of renal acidification. In dogs, a new steady state emerges within 3 to 5 days. Whether this temporal pattern applies to humans is unknown. In patients, chronic hypercapnia often reflects gradual deterioration in pulmonary function; consequently, the secondary response might keep pace with the slowly rising PaCO₂ without a perceptible delay. Careful observations of patients with chronic hypercapnia as a result of chronic obstructive pulmonary disease allowed estimation of a mean Δ[HCO₃⁻]/ΔPaCO₂ slope of 0.35 mEq/L per mmHg; expected [HCO₃⁻] = 24 + ([current PaCO₂ - 40] × 0.35). This slope functions up to a PaCO₂ of approximately 70 mmHg. Beyond that level, the slope of Δ[HCO₃⁻]/ΔPaCO₂ seems to flatten. More recently, a substantially larger slope was reported, but the small number of blood gas measurements, one for each of 18 patients, calls into question the validity of the conclusion reached.

Respiratory Acidosis

- Hypocapnia alkalinizes body fluids and stimulates nonbicarbonate buffers, yielding a decrease in plasma [HCO₃⁻]. This secondary hypobicarbonatemic response is completed within 5 to 10 minutes and remains stable for several hours. Hypocapnia of 20 to 120 minutes’ duration resulting from either voluntary hyperventilation in normal individuals or controlled hyperventilation in anesthetized patients undergoing minor surgical procedures yielded a mean Δ[HCO₃⁻]/ΔPaCO₂ slope of 0.2 mEq/L per mmHg; expected [HCO₃⁻] = 24 - ([40 - current PaCO₂] × 0.2). Sustained hypocapnia causes an additional decrease in plasma [HCO₃⁻] owing to suppression of renal acidification. A new steady state emerges within 2 to 3 days. Studies of normal volunteers who were exposed to hypobaric hypoxia (6 days) and unanesthetized patients who had spinal cord or head injuries and were undergoing controlled hyperventilation (7 to 11 days) revealed a mean Δ[HCO₃⁻]/ΔPaCO₂ slope of 0.4 mEq/L per mmHg; expected [HCO₃⁻] = 24 - ([40 - current PaCO₂] × 0.4).

Metabolic Acidosis

- Primary hypobicarbonatemia engenders acidemia that stimulates central and peripheral chemoreceptors, causing increases in tidal volume and, usually, respiratory rate. This secondary hypocapnic response consistently attends metabolic acidosis, whether induced in normal volunteers who are administered ammonium chloride or observed in patients with various disorders, such as diarrhea, disturbances of intermediary metabolism, or renal failure. Although the magnitude of the ventilatory response varies considerably among studies, it seems to be independent of the cause of the acidosis. Compiling most published studies, a mean ΔPaCO₂/Δ[HCO₃⁻] slope of 1.2 mmHg per mEq/L is obtained; expected PaCO₂ = 40 - ([24 - current HCO₃⁻] × 1.2).

The secondary response appears within 30 to 120 minutes from onset of metabolic acidosis; the time interval for its completion (and its disappearance after correction of the metabolic acidosis) depends on the pace of development of the disorder. In patients with cholera, when plasma [HCO₃⁻] falls or corrects slowly, such as by 6 mEq/L in 24 hours, the ventilatory response keeps pace with the level of plasma [HCO₃⁻]. Conversely, when metabolic acidosis develops or corrects rapidly, 11 to 24 hours is required for the ventilatory response to reach completion or vanish.

Table 1. Secondary responses to alterations in acid-base status

<table>
<thead>
<tr>
<th>Disorder</th>
<th>Primary Change</th>
<th>Secondary Response</th>
<th>Mean Slope of the Secondary Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiratory acidosis</td>
<td>PaCO₂</td>
<td>[HCO₃⁻]</td>
<td>Δ[HCO₃⁻]/ΔPaCO₂ = 0.1 mEq/L per mmHg; expected [HCO₃⁻] = 24 + ([current PaCO₂ - 40] × 0.1)</td>
</tr>
<tr>
<td>chronic</td>
<td>]</td>
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<td>]</td>
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</tr>
<tr>
<td>acute</td>
<td>]</td>
<td>[</td>
<td>]</td>
</tr>
<tr>
<td>chronic</td>
<td>]</td>
<td>[</td>
<td>]</td>
</tr>
<tr>
<td>Metabolic acidosis</td>
<td>[HCO₃⁻]</td>
<td>PaCO₂</td>
<td>ΔPaCO₂/Δ[HCO₃⁻] = 1.2 mmHg per mEq/L</td>
</tr>
<tr>
<td>Metabolic alkalosis</td>
<td>[HCO₃⁻]</td>
<td>PaCO₂</td>
<td>ΔPaCO₂/Δ[HCO₃⁻] = 0.7 mmHg per mEq/L</td>
</tr>
</tbody>
</table>

The term “acute” refers to a duration of minutes to several hours. The term “chronic” refers to a duration of several days or longer.

studies for each disorder and weighed study design, methods, and evidence of a steady state. One can think of these as general rules for secondary responses. Because of space constraints, we cite only limited references.
reduction in tidal volume. Observations of humans with metabolic alkalosis owing to diuretic use, vomiting, or gastric suction yielded a mean $\Delta\text{PaCO}_2/\Delta[\text{HCO}_3^-]$ slope of 0.7 mmHg per mEq/L; expected $\text{PaCO}_2 = 40 + [(\text{current } \text{HCO}_3^- - 24) \times 0.7]$. Contrary to early views, neither hypoxemia nor potassium depletion prevents expression of this response. The requisite time for development of the secondary hypercapnia remains uncertain. Although studies indicate that full expression of the hypoventilatory response requires 24 to 36 hours, such a lag might not occur in patients who develop metabolic alkalosis at a slow pace.

CAVEATS

In assessing the appropriateness of the secondary response to an acid-base disorder, there are several caveats.

Time Course

As noted, considerable uncertainty exists regarding the time course for completion and eradication of the secondary responses in humans. A mixed acid-base disorder might be diagnosed incorrectly because insufficient time has elapsed for the secondary response to a single primary disorder to develop or resolve.

Confidence Intervals

Empirical data have been used to construct confidence intervals that define the limits of the secondary response to each acid-base disorder. In clinical practice, these limits can be taken as ±3 mEq/L for plasma [HCO$_3^-$] and ±5 mmHg for PaCO$_2$, from the values calculated from the mean, steady-state slopes (Table 1). Values falling outside these limits denote the presence of a mixed acid-base disorder. Importantly, values falling within the limits of the secondary response can be interpreted as consistent with but not diagnostic of a particular disorder. In fact, a given set of acid-base values is never diagnostic of a specific acid-base disorder; clinical correlation is always required to establish the correct diagnosis. Interpretation of acid-base data of patients undergoing ventilator support must consider that this procedure sets the PaCO$_2$ level and thus has the potential of altering preexisting acid-base status, whether normal or abnormal.

Impact of Preexisting Acid-Base Disorders

Clinicians tend to apply equally the slopes depicted in Table 1 to patients presumed to have a single acid-base disorder and those with mixed disorders. This practice assumes preexisting acid-base disorders do not influence the secondary response to superimposed disorders. Extensive studies of the dog demonstrate this supposition is largely erroneous. The $\Delta[\text{HCO}_3^-]/\Delta\text{PaCO}_2$ response to acute hypocapnia in dogs with background metabolic acidosis or chronic respiratory alkalosis is larger than that in normal animals, whereas this response is smaller than normal in dogs with preexisting metabolic alkalosis or chronic respiratory acidosis.27,28 Similarly, the $\Delta[\text{HCO}_3^-]/\Delta\text{PaCO}_2$ response to chronic respiratory acidosis is larger in dogs with underlying metabolic acidosis and smaller in those with background metabolic alkalosis than in normal dogs.29,30 Normal dogs and dogs with background metabolic acidoses have an identical secondary response to chronic hypocapnia, but this response is much larger in dogs with underlying metabolic alkalosis.13,31,32 It is highly probable but still unknown whether humans exhibit a similar response to that demonstrated in dogs. Consequently, the direct applicability of the slopes depicted in Table 1 to patients with mixed acid-base disorders is uncertain.

Hybrid Nature of Plasma [HCO$_3^-$] in Metabolic Disorders

It is generally assumed that changes in PaCO$_2$ that attend metabolic disorders have no impact on plasma [HCO$_3^-$] other than the small change occurring as a consequence of buffering; however, this formulation assumes that the kidney has a way to discriminate between primary and secondary changes in PaCO$_2$, mounting a vigorous acidification response to the former, as reflected in the $\Delta[\text{HCO}_3^-]/\Delta\text{PaCO}_2$ slopes of chronic respiratory alkalosis and chronic respiratory acidosis (Table 1) but remaining indifferent to the latter. This formulation proves fallacious in studies of dogs with metabolic acidosis or metabolic alkalosis, in which the kidney elicits major acidification responses to the prevailing metabolic acidosis or alkalosis.

![Figure 1](image)

**Figure 1.** Pathophysiologic basis of the change in plasma [HCO$_3^-$] in metabolic acidosis (left) and metabolic alkalosis (right) in the dog. Only a part of the change in plasma [HCO$_3^-$] is attributed to the primary metabolic process. The remainder, approximately 40% of the overall change, is due to adjustments in renal acidification engendered by the associated secondary hypocapnia or hypercapnia. These renal responses are maladaptive because they undermine the salutary effect on blood pH afforded by the ventilatory responses acutely. Based on data from Madias and colleagues.30,33
secondary hypocapnia or hypercapnia. Indeed, fully 40% of the overall change in plasma [HCO₃⁻] in metabolic disorders results not from the metabolic processes themselves, particularly the acid load in metabolic acidosis or volume and Cl⁻ deficits in metabolic alkalosis, but from the indiscriminate responses of the kidney to secondary changes in PaCO₂ (Figure 1).30,33 These renal responses are maladaptive because they undermine the salutary effect on blood pH afforded by the ventilatory responses acutely. Indeed, under certain conditions, this maladaptation nullifies a beneficial impact or even yields a more abnormal pH than would occur in the complete absence of a ventilatory response. The similarity of the acidification processes between dogs and humans suggests strongly that these observations are also applicable to humans; however, until the requisite studies are carried out, such extrapolations must remain conjectural.

DISCLOSURES

None.

REFERENCES