A Short Guide to Acid-Base Balance

Year after year this topic seems to perplex even the very best of medical students and junior doctors alike. Often over-complicated, this topic really isn’t that hard to understand as long as a few basic concepts are understood. I promise that by the end of this short tutorial you will have learnt all you need to know about acid base balance in order to be competent in interpreting arterial blood gases (ABG), something that will help you no end with your management of acutely ill patients.

The pH of blood is maintained at an optimum physiological level of 7.35-7.45. It affects all basic cellular functions and as it shifts outside of this range, so the function of all the bodies’ organs become compromised. We have evolved various mechanisms in order to keep the blood pH fairly constant.

Let’s revisit some basics.........

An understanding of the various, often over-complicated, pH formulae are not needed in order to be competent at understanding arterial blood gases. Essentially as far as we are concerned, when talking about pH in the context of acid base, it is used as a measure of how acidic/alkaline the blood is. In other words it represents the concentration of hydrogen ions in blood. One should bear in mind that the scale itself is a reverse logarithmic representation of the hydrogen concentration and so as the number of hydrogen ions rises 10-fold, the pH drops by one, and as the hydrogen concentration rises by 100-fold, the pH drops by 2 and so on.

The main players in acid base balance

The two main systems involved in maintaining acid base balance are the respiratory and renal systems.

Kidneys: Carbon dioxide, water and hydrogen are all produced by metabolism of proteins, carbohydrates and fats. The hydrogen ions are buffered in the blood by bicarbonate, along with haemoglobin and phosphate. The hydrogen ions are excreted by the kidneys in order to help maintain blood pH.

Lungs: Carbon dioxide levels are detected in the hypothalamus by chemoreceptors, adjusting the rate and depth of respiration accordingly, in order to help maintain a normal pH.

The all important formula

The following formula is vital in understanding how the lungs and kidneys regulate acid base. By working together these two systems help keep the pH fairly constant. As will become clear, one system can compensate for the other in times of pathology, to keep the pH between the normal levels of 7.35 - 7.45.

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ 
\]
The left hand side of the equation is dependent on the respiratory system, which alters the amount of CO₂ there is in the blood. If, for example, the respiratory rate or depth of breathing were to decrease, the amount of CO₂ in the blood would increase, driving the formula to the right hand side. This would increase the hydrogen concentration and lower the pH.

Alternatively, if the kidneys were less able to excrete hydrogen ions, the equation would shift to the left and increase the amount of CO₂ in the blood.

(The various sites and mechanisms of bicarbonate and hydrogen regulation in the kidney are not described here since it is available in any medicine textbook and is not important here for the basic understanding of acid base balance. Essentially the kidneys help regulate blood pH by reabsorbing bicarbonate and excreting and reabsorbing hydrogen ions.)

Let's now see how some clinical conditions affect the acid base balance

Acidosis and alkalosis are clinical terms used to describe a blood pH level below and above the normal pH range of 7.35-7.45 respectively.

Clinical examples:

**Respiratory alkalosis**

This would be seen in a patient who is over-breathing, for example a patient hyperventilating. This hyperventilation could be voluntary, due to stimulation of the respiratory centre or due to artificial ventilation. How would over breathing affect the blood pH?

As breathing increases, CO₂ is blown off causing the equation to shift to the left. This increases the pH since the hydrogen ion concentration falls in order to make the CO₂ that is being blown off and hence the pH rises, causing an alkalosis.

**Clinical example (1):**

Mr Jones, a 22 year old man who has a respiratory rate or 45 presents after having a panic attack on an over-crowded tube. You, the F1 doctor, are asked by the registrar to do an arterial blood gas. The following result is obtained:
pH  7.55  
pCO₂  2.2  
pO₂   15.1

**Interpretation:**

No matter what the clinical scenario, always ask yourself the same set of questions:

1) Is the pH normal? If not is it an acidosis or an alkalosis?
2) Does the pCO₂ level explain the pH change?

In the scenario above, the pH is above normal indicating an alkalosis. The low pCO₂ would explain the pH change. This confirms that it is a respiratory fault resulting in a change in the blood pH.

**Other things in the blood gas result.......**

So far we have only mentioned pH, CO₂ and O₂ when interpreting blood gases. However, there are a couple of other values that are given on an arterial blood gas printout that can help with its interpretation:

Bicarbonate levels are usually in the range of 22-30mmol. If the pH were to rise, so an acidosis was present, the kidneys would reabsorb more bicarbonate in order to try to shift the curve to the left and allow the lungs to blow off more CO₂.

Remember the following formula:

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+ \\
\]

However, the bicarbonate level in example 1 above would probably be normal as it takes a while for the kidneys to start to make the changes. As we will see later, this can give us clues as to how long a patient has been alkalotic or acidotic by whether or not the kidneys have had time to compensate for the changes.

Base excess is also shown on the printout. This is defined as the amount of H ions that would be needed to return the blood pH to 7.35, if the pCO₂ were adjusted to a normal value. In the calculation, any change in pH due to a change in pCO₂ is eliminated and hence any pH change reflects only the metabolic component of the acid base disturbance. Normal value for base excess is -2 - +2.
Respiratory Acidosis

This would be seen in a patient with any of the following:

- poor lung perfusion
- impaired gas exchange
- decreased ventilation

How would this affect the pH?

As less CO₂ is blown off (for any one of the reasons mentioned above), the concentration rises, shifting the equation to the right, increasing the H⁺ concentration and hence decreasing the pH and causing an acidosis.

Clinical example (2):

Mrs Parker, a 58 year old obese lady presents with sudden onset of chest pain with shortness of breath. On examination you, the newly qualified F1 working in A and E remember to check the legs and find that her right calf is swollen and tense. You suspect a pulmonary embolism (PE) secondary to a deep vein thrombosis (DVT) and perform an ABG. The following result is obtained:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.21</td>
</tr>
<tr>
<td>pCO₂</td>
<td>9.8</td>
</tr>
<tr>
<td>pO₂</td>
<td>7.7</td>
</tr>
<tr>
<td>bicarbonate</td>
<td>28</td>
</tr>
<tr>
<td>base excess</td>
<td>-1</td>
</tr>
</tbody>
</table>

Interpretation:

No matter what the clinical scenario, always ask yourself the same set of questions:

1) Is the pH normal? If not is it an acidosis or an alkalosis?
2) Does the PCO₂ level explain the pH change?

In the scenario above, the pH is below normal indicating an acidosis. The high pCO₂ would explain the pH change. This confirms that it is a respiratory fault resulting in a change in the blood pH.
This is the typical result for a respiratory acidosis. The PE has decreased the perfusion of the lungs resulting in an increase CO₂ blood concentration. This drives the formula to the right, which increases the H⁺ concentration decreasing the pH. The pO₂ is lower than normal which would be expected in a PE.

**Metabolic Acidosis**

This would be seen in a patient with any of the following:

- Increased H⁺ production i.e. diabetic ketoacidosis
- Decreased H⁺ loss i.e. renal failure
- Loss of bicarbonate i.e. vomiting

How would this affect the pH?

The pH will fall in any of the above disorders, causing a blood acidosis.

In order to understand how the body deals with this we need to consider a process known as compensation.

**Compensation**

\[ \text{CO}_2 + \text{H}_2\text{O} \xleftrightarrow{} \text{H}_2\text{CO}_3 \xleftrightarrow{} \text{HCO}_3^- + \text{H}^+ \]

An increase in H⁺ would shift the formula to the left causing an increase in CO₂. Since the lungs respond immediately to changes in CO₂ levels, they are stimulated to increase the rate and depth of respiration. This blows off the excess CO₂ and helps return the pH towards normal. The lungs are said to be compensating for the metabolic acidosis, in that they are helping to restore the normal pH. This is known as a metabolic acidosis with respiratory compensation.

**Clinical example (3):**

Mr Shah, a 21 year old man presents with vomiting and abdominal pain. He is a known type I diabetic and has had several admissions for diabetic ketoacidosis (DKA). He is breathing heavily and you decide to do an ABG. The following result is obtained:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Normal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.27</td>
<td>(7.35-7.45)</td>
</tr>
<tr>
<td>pCO₂</td>
<td>3.2</td>
<td>(4.7-6.0 KPa)</td>
</tr>
<tr>
<td>pO₂</td>
<td>14.1</td>
<td>(&gt;10.6 KPa)</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>11</td>
<td>(22-30 mmol)</td>
</tr>
<tr>
<td>Base Excess</td>
<td>-15</td>
<td>(-2+2)</td>
</tr>
</tbody>
</table>
Interpretation:

No matter what the clinical scenario, always ask yourself the same set of questions:

1) Is the pH normal? If not is it an acidosis or an alkalosis?
2) Does the pCO₂ level explain the pH change?
3) If the pCO₂ does not explain it, does the bicarbonate and base excess show a metabolic cause?
4) Is the pCO₂ within normal range? Or is it compensating for a metabolic problem?

In clinical example 3 the pH is lower than normal indicating an acidosis. We need to decide if it is a respiratory problem or a metabolic one causing the acidosis. The pCO₂ is lower than normal which cannot explain the low pH, and so we know it is not a primary respiratory problem causing the acidosis. The bicarbonate and base excess are both lower than expected indicating that there is a metabolic acidosis. The reason for the low pCO₂ is that the respiratory system is trying to compensate for this acidosis by blowing off more. Compensation is often incomplete and so although the pH is still low, it would be a lot lower without the respiratory compensation.

Metabolic alkalosis

This would be seen in a patient with any of the following:

- H⁺ loss i.e. vomiting
- bicarbonate ingestion

How would this affect the pH?

The pH will rise in any of the above disorders, causing a blood alkalosis.

Compensation

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+
\]

A decrease in H⁺ would shift the formula to the right causing a decrease in CO₂. Since the lungs respond immediately to changes in CO₂ levels, the respiratory centre will signal a decrease in the rate and depth of respiration in order to allow the CO₂ to rise and help restore the pH. The lungs are said to be compensating for the metabolic alkalosis, in that they are helping to restore the normal pH. This is called a metabolic alkalosis with respiratory compensation.
Clinical example (4):

Mr Blake, a 19 year old student presents with severe vomiting. He vaguely remembers eating a kebab on the way home from the pub the night before. You do an ABG to determine if there is any acid base imbalance. The following result is obtained:

- pH: 7.53 (7.35-7.45)
- pCO₂: 8.0 (4.7-6.0 KPa)
- pO₂: 12.1 (>10.6 KPa)
- Bicarbonate: 57 (22-30 mmol)
- Base Excess: +24 (-2-+2)

Interpretation:

No matter what the clinical scenario, always ask yourself the same set of questions:

1) Is the pH normal? If not is it an acidosis or an alkalosis?
2) Does the pCO₂ level explain the pH change?
3) If the pCO₂ does not explain it, does the bicarbonate and base excess show a metabolic cause?
4) Is the pCO₂ within normal range? Or is it compensating for a metabolic problem?

In clinical example 4 the pH is higher than normal indicating an alkalosis. We need to decide if it is a respiratory or a metabolic problem. The pCO₂ is higher than normal which cannot explain the high pH, and so we know it is not a primary respiratory problem causing the alkalosis. The bicarbonate and base excess are both higher than expected indicating that there is a metabolic alkalosis. The reason for the high CO₂ is that the respiratory system is trying to compensate by reducing the rate and depth in order to increase the blood CO₂ and help reduce the pH. Again, the compensation is not complete as the pH is still outside of the normal range.

Respiratory versus metabolic compensation

We have already seen that the respiratory system can compensate for metabolic acid base disturbances by altering the rate and depth of breathing. This occurs immediately as soon as the peripheral and central chemoreceptors detect CO₂ levels.

The renal system is also able to compensate when the respiratory system is impaired. It does this by altering the amount of bicarbonate and H⁺ it reabsorbs and excretes. However, unlike respiratory compensation this does not occur immediately and may take up to 2 days to start to compensate. This can give important information when interpreting ABG’s.

Let’s look at the following two blood gas results, both of which show a respiratory impairment.
In the case of a PE, it is a sudden event and a person presenting immediately may show a similar picture to that in the first column. Since it is an acute event, the kidneys have not had time to compensate and so the pH remains low whilst the bicarbonate and base excess are normal. However, in the case of a chronic respiratory condition such as pulmonary fibrosis, the pH may well be normal even though the pCO₂ is high. This is because the kidneys have had time to start to compensate by reabsorbing more bicarbonate to increase the pH.

**Summary**

We have seen how the lungs and kidneys work together in order to keep blood pH constant. When there is pathology in one system, the other can often compensate.

Arterial blood gas analysis is a fantastic way of assessing what is happening with the acid base balance and is used in a whole range of clinical situations in order to get a quick assessment of how severe a particular condition is. Particulalry good in respiratory impairment, it is the only real way of getting a true picture of what is going on with the respiratory system and supersedes oxygen saturation probe monitoring.

No matter how complicated the interpretation seems, if you remember a few basic facts when interpreting any ABG result then they will make a lot more sense. Remember to see if the pH is normal and if it is not, to see if the pCO₂ level correlates with the change (indicating a primary respiratory problem) or not (indicating a primary metabolic problem). Then see if there is any compensation and hence determine if the problem is an acute or chronic one.

Remember that respiratory compensation can occur immediately but metabolic compensation may take up to 2 days to take effect.

**Test Yourself**

Now test yourself below to see if have a full understanding of how to interpret acid base imbalances.

**For each of the following examples, choose from the following options:**

(a) Respiratory acidosis
(b) Respiratory alkalosis
(c) Metabolic acidosis
(d) Metabolic alkalosis
(e) Respiratory acidosis with metabolic compensation
(f) Respiratory alkalosis with metabolic compensation
(g) Metabolic acidosis with respiratory compensation
(h) Metabolic alkalosis with respiratory compensation

<table>
<thead>
<tr>
<th></th>
<th>Acute (eg pulmonary embolism)</th>
<th>Chronic (eg. pulmonary fibrosis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.21</td>
<td>7.36 (7.35-7.45)</td>
</tr>
<tr>
<td>pCO₂</td>
<td>9.0</td>
<td>9.0 (4.7-6.0 KPa)</td>
</tr>
<tr>
<td>pO₂</td>
<td>7.8</td>
<td>7.8 (&gt;10.6 KPa)</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>27</td>
<td>35 (22-30 mmol)</td>
</tr>
<tr>
<td>Base Excess</td>
<td>-1</td>
<td>+6 (-2+-2)</td>
</tr>
</tbody>
</table>
(1)
| pH   | 7.26 |
| pCO₂ | 3.3  |
| pO₂  | 14.0 |
| Bicarbonate | 12 |
| Base Excess     | -14 |

(2)
| pH   | 7.55 |
| pCO₂ | 2.2  |
| pO₂  | 15.1 |
| Bicarbonate | 26 |
| Base Excess     | +1  |

(3)
| pH   | 7.20 |
| pCO₂ | 9.9  |
| pO₂  | 7.6  |
| Bicarbonate | 29 |
| Base Excess     | -1  |

(4)
| pH   | 7.52 |
| pCO₂ | 8.1  |
| pO₂  | 12.0 |
| Bicarbonate | 56 |
| Base Excess     | +25 |

(5)
| pH   | 7.31 |
| pCO₂ | 9.8  |
| pO₂  | 7.7  |
| Bicarbonate | 38 |
| Base Excess     | -8  |

(6)
| pH   | 7.34 |
| pCO₂ | 3.4  |
| pO₂  | 13   |
| Bicarbonate | 18 |
| Base Excess     | -8  |

(Answers overleaf)

Tip: A favourite acid base question in exams is that of the aspirin overdose. If you apply the simple rules we have gone through you may still end up confused. That is because this is one of the rarer cases where you see a mixed picture, both respiratory alkalosis and metabolic acidosis. The reason is that salicylates stimulate the respiratory centre causing a respiratory alkalosis. They also uncouple oxidative phosphorylation leading to a build up of organic acids causing a metabolic acidosis.
Answers

1 g
2 b
3 a
4 h
5 e
6 g

Note
These notes were written by James Stokes, as a final year medical student in 2007. They are presented in good faith and every effort has been taken to ensure their accuracy. Nevertheless, medical practice changes over time and it is always important to check the information with your clinical teachers and with other reliable sources. Disclaimer: no responsibility can be taken by either the author or publisher for any loss, damage or injury occasioned to any person acting or refraining from action as a result of this information.