CHAPTER 3
Acid–base balance

By the end of this chapter you will be able to:

• Understand how the body maintains a narrow pH
• Know the meaning of common terms used in arterial blood gas analysis
• Know the causes of acid–base abnormalities
• Use a simple system to interpret arterial blood gases
• Understand why arterial blood gases are an important test in critical illness
• Apply this to your clinical practice

Acid as a by-product of metabolism

The human body is continually producing acid as a by-product of metabolism. But it must also maintain a narrow pH range, necessary for normal enzyme activity and the millions of chemical reactions that take place in the body each day. Normal blood pH is 7.35–7.45 and this is maintained by:

• Intracellular buffers (e.g. proteins and phosphate)
• Extracellular buffers (e.g. plasma proteins, haemoglobin and carbonic acid/bicarbonate)
• Finally, the excretory functions of the kidneys and lungs.

A buffer is a substance that resists pH change by absorbing or releasing hydrogen ions (H⁺) when acid or base is added to it. The intracellular and extracellular buffers absorb H⁺ ions and transport them to the kidneys for elimination. The carbonic acid/bicarbonate system allows H⁺ ions to react with bicarbonate to produce carbon dioxide (CO₂) and water and the CO₂ is eliminated by the lungs:

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

carbonic anhydrase (enzyme)

Carbonic acid (H₂CO₃) continually breaks down to form CO₂ and water, hence this system always tends to move in a rightward direction and, unlike other buffer systems, never gets saturated. But it is easy to see how, for example, a problem with ventilation would quickly lead to a build-up of CO₂, a respiratory acidosis. Uniquely, the components of the carbonic acid/bicarbonate system can be adjusted independently of one another. The kidneys can regulate H⁺ ions excretion in the urine and CO₂ levels can be adjusted by changing ventilation. The excretory functions of the lungs and kidneys are connected by carbonic acid so that if one organ becomes overwhelmed, the other can ‘help’ or ‘compensate’.
The lungs have a simple way of regulating CO₂ excretion, but the kidneys have three main ways of excreting H⁺ ions:

1. Mainly by regulating the amount of bicarbonate (HCO₃⁻) absorbed in the proximal tubule.
2. By the reaction HPO₄²⁻ + H⁺ → H₂PO₄⁻. The H⁺ ions come from carbonic acid, leaving HCO₃⁻ which passes into the blood.
3. By combining ammonia with H⁺ ions from carbonic acid. The resulting ammonium ions cannot pass back into the cells and are excreted.

The kidney produces bicarbonate (HCO₃⁻) which reacts with free H⁺ ions. This is why the bicarbonate level is low when there is an excess of H⁺ ions or a metabolic acidosis.

In summary, the body is continually producing acid, yet at the same time must maintain a narrow pH range in order to function effectively. It does this by means of buffers and then the excretory functions of the lungs (CO₂) and kidneys (H⁺). It follows therefore that acid–base disturbances occur when there is a problem with ventilation, a problem with renal function, or an overwhelming acid or base load the body cannot handle.

**Some definitions**

Before moving on, it is important to understand some important definitions regarding arterial blood gases:

- **Acidaemia or alkalaemia**: a low or high pH.
- **Acidosis**: a process which leads to acidaemia (e.g. high PaCO₂ or excess H⁺ ions (low bicarbonate)).
- **Alkalosis**: a process which leads to alkalaemia (e.g. low PaCO₂ or high bicarbonate).
- **Compensation**: normal acid–base balance is a normal pH plus a normal PaCO₂ and normal bicarbonate. Compensation is when there is a normal pH but the bicarbonate and PaCO₂ are abnormal.
- **Correction**: the restoration of normal pH, PaCO₂ and bicarbonate.
- **Base excess (BE)**: this measures how much extra acid or base is in the system as a result of a metabolic problem. It is calculated by measuring the amount of strong acid that has to be added to a sample to produce a pH of 7.4. A minus figure means the sample is already acidotic so no acid had to be added. A plus figure means the sample is alkalotic and acid had to be added. The normal range is -2 to +2. A minus BE is often termed a ‘base deficit’.
- **Actual vs standard bicarbonate**: a problem with ventilation would quickly lead to a build-up of CO₂ or a respiratory acidosis. This CO₂ reacts with water to produce H⁺ and HCO₃⁻, and therefore causes a small and immediate rise in bicarbonate. The standard bicarbonate is calculated by the blood gas analyser from the actual bicarbonate, but assuming 37°C and a normal PaCO₂ of 5.3 kPa (40 mmHg). Standard bicarbonate therefore reflects the metabolic component of acid–base balance, as opposed to any changes in bicarbonate that have occurred as a result of a respiratory problem. Some
blood gas machines only report the actual bicarbonate, in which case you should use the BE to examine the metabolic component of acid–base balance. Otherwise, the standard bicarbonate and BE are interchangeable.

*Note:* If you do not like equations, skip the box below.

**Box 3.1 pH and the Henderson–Hasselbach equation**

Everyone has heard of the Henderson–Hasselbach equation, but what is it? $\text{H}^+$ ions are difficult to measure as there are literally billions of them. We use pH instead, which, simply put, is the negative logarithm of the $\text{H}^+$ ion concentration in moles:

$$\text{pH} = -\log[\text{H}^+]$$

When carbonic ($\text{H}_2\text{CO}_3$) acid dissociates:

$$\text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-$$

the product of $[\text{H}^+]$ and $[\text{HCO}_3^-]$ divided by $[\text{H}_2\text{CO}_3]$ remains constant. Put in equation form:

$$\text{K}_a = \frac{[\text{H}^+][\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]}$$

$\text{K}_a$ is the dissociation constant. $p\text{K}_a$ is like pH, it is the negative logarithm of $\text{K}_a$. The Henderson–Hasselbach equation puts the pH and the dissociation equations together, and describes the relationship between pH and the molal concentrations of the dissociated and undissociated form of carbonic acid:

$$\text{pH} = p\text{K}_a + \log\left(\frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]}\right)$$

Since $[\text{H}_2\text{CO}_3]$ is related to $\text{PaCO}_2$, a simplified version is:

$$\text{pH} = \log\left(\frac{[\text{HCO}_3^-]}{\text{PaCO}_2}\right)$$

This simple relationship can be used to check the consistency of arterial blood gas data. If we know that pH (or the concentration of $\text{H}^+$ ions) is related to the ratio of $\text{HCO}_3^-$ and $\text{PaCO}_2$, it should be easy to check whether a blood gas result is ‘real’ or not, or the result of laboratory error (see Appendix at the end of this chapter).
Common causes of acid–base disturbances

As previously mentioned, acid–base disturbances occur when there is:
• A problem with ventilation
• A problem with renal function
• An overwhelming acid or base load the body cannot handle.

Respiratory acidosis

Respiratory acidosis is caused by acute or chronic alveolar hypoventilation. The causes are described in Chapter 2 and include upper or lower airway obstruction, reduced lung compliance from infection, oedema, trauma or obesity and anything that causes respiratory muscle weakness, including fatigue.

In an acute respiratory acidosis, cellular buffering is effective within minutes to hours. Renal compensation takes 3–5 days to be fully effective. We know from human volunteer studies [1] by how much the standard bicarbonate rises as part of the compensatory response. Although doctors do not frequently use these figures in everyday practice, having a rough idea is nevertheless useful (see Fig. 3.1).

Respiratory alkalosis

Respiratory alkalosis is caused by alveolar hyperventilation, the opposite of respiratory acidosis, and is nearly always accompanied by an increased respiratory rate. Again, renal compensation takes up to 5 days to be fully effective, by excreting bicarbonate in the urine and retaining H⁺ ions. When asked what causes hyperventilation, junior doctors invariably reply ‘hystera’. In fact, hyperventilation is a sign, not a diagnosis and has many causes:
• Lung causes: bronchospasm, hypoxaemia, pulmonary embolism, pneumonia, pneumothorax, pulmonary oedema

<table>
<thead>
<tr>
<th>Primary change</th>
<th>Compensatory response</th>
</tr>
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<tbody>
<tr>
<td>Metabolic acidosis</td>
<td>↓ [HCO₃⁻]</td>
</tr>
<tr>
<td>Metabolic alkalosis</td>
<td>↑ [HCO₃⁻]</td>
</tr>
<tr>
<td>Acute respiratory acidosis</td>
<td>↑ (\text{PaCO}_2)</td>
</tr>
<tr>
<td>Chronic respiratory acidosis</td>
<td>↑ (\text{PaCO}_2)</td>
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<td>Acute respiratory alkalosis</td>
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<tr>
<td>Chronic respiratory alkalosis</td>
<td>↓ (\text{PaCO}_2)</td>
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</tbody>
</table>

Figure 3.1 Renal and respiratory compensation. Reproduced with permission from McGraw-Hill Publishers [1].
• Central nervous system causes: meningitis/encephalitis, raised intracranial pressure, stroke, cerebral haemorrhage
• Metabolic causes: fever, hyperthyroidism
• Drugs (e.g. salicylate poisoning)
• Psychogenic causes: pain, anxiety.

**Metabolic acidosis**

Metabolic acidosis most commonly arises from an overwhelming acid load. Respiratory compensation occurs within minutes. Maximal compensation occurs within 12–24 h, but respiratory compensation is limited by the work involved in breathing and the systemic effects of a low CO₂ (mainly cerebral vasoconstriction). It is unusual for the body to be able to fully compensate for a metabolic acidosis.

There are many potential causes of a metabolic acidosis, so it is important to subdivide these into metabolic acidosis with an increased anion gap or metabolic acidosis with a normal anion gap. In general, a metabolic acidosis with an increased anion gap is caused by the body gaining acid, whereas a metabolic acidosis with a normal anion gap is caused by the body losing base.

**The anion gap**

Blood tests measure most cations (positively charged molecules) but only a few anions (negatively charged molecules). Anions and cations are equal in the human body, but if all the measured cations and anions are added together there would be a gap – this reflects the concentration of those anions not measured, mainly plasma proteins. This is called the anion gap and is calculated from a blood sample:

\[(\text{sodium + potassium}) - (\text{chloride + bicarbonate})\]

The normal range for the anion gap is 15–20 mmol/l, but this varies from one laboratory to another and should be adjusted downwards in patients with a low albumin (by 2.5 mmol/l for every 1 g/dl fall in plasma albumin). Similarly, a fall in any unmeasured cations (e.g. calcium or magnesium) may produce a spurious increase in the anion gap.

Some patients may have more than one reason to have a metabolic acidosis (e.g. diarrhoea leading to loss of bicarbonate plus severe sepsis and hypoperfusion). Many blood gas machines calculate the anion gap but if not, it should always be calculated when there is a metabolic acidosis, as this helps to narrow down the cause. The base deficit is known to correlate with mortality [2]. A severe metabolic acidosis indicates critical illness.

**Metabolic acidosis with an increased anion gap**

In a metabolic acidosis with an increased anion gap, the body has gained acid through:
• Ingestion
• The body’s own production
• An inability to excrete it
Common clinical causes are:

- **Ingestion:** salicylate, methanol/ethylene glycol, tricyclic antidepressant poisoning
- **Lactic acidosis type A** (anaerobic tissue metabolism): any condition causing tissue hypoperfusion, either global (e.g. shock, cardiac arrest) or local (e.g. intra-abdominal ischaemia)
- **Lactic acidosis type B** (liver dysfunction): reduced lactate metabolism in liver failure, metformin (rare)
- **Ketoacidosis:** insulin deficiency (diabetic ketoacidosis), starvation
- **Renal failure**
- **Massive rhabdomyolysis** (damaged cells release $\text{H}^+$ ions and organic anions).

**Metabolic acidosis with a normal anion gap**

In a metabolic acidosis with a normal anion gap, bicarbonate is lost via the kidneys or the gastrointestinal tract. Occasionally reduced renal $\text{H}^+$ ions excretion is the cause. A normal anion gap metabolic acidosis is sometimes also called ‘hyperchloraemic acidosis’. Common clinical causes are:

- **Renal tubular acidosis**
- **Diarrhoea, fistula or ileostomy**
- **Acetazolomide therapy.**

Overall, the most common cause of a metabolic acidosis in hospital is tissue hypoperfusion. Oxygen and fluid resuscitation are important aspects of treatment, as well as treatment of the underlying cause.

**Metabolic alkalosis**

Metabolic alkalosis is the least well known of the acid–base disturbances. It can be divided into two groups: saline responsive and saline unresponsive. Saline responsive metabolic alkalosis is the most common and occurs with volume contraction (e.g. vomiting or diuretic use). Gastric outflow obstruction is a well-known cause of ‘hypokalaemic hypochloraemic metabolic alkalosis’. Excessive vomiting or nasogastric suction leads to loss of hydrochloric acid, but the decline in glomerular filtration rate which accompanies this perpetuates the metabolic alkalosis. The kidneys try to reabsorb chloride (hence the urine levels are low), but there is less of it from loss of hydrochloric acid, so the only available anion to be reabsorbed is bicarbonate. Metabolic alkalosis is often associated with hypokalaemia, due to secondary hyperaldosteronism from volume depletion.

Another relatively common cause of saline responsive metabolic alkalosis is when hypercapnia is corrected quickly by mechanical ventilation. Posthypercapnia alkalosis occurs because a high $\text{PaCO}_2$ directly affects the proximal tubules and decreases sodium chloride reabsorption leading to volume depletion. If chronic hypercapnia is corrected rapidly with mechanical ventilation, metabolic alkalosis ensues because there is already a high bicarbonate and the kidney needs time to excrete it. The pH change causes a shift in potassium with resulting hypokalaemia and sometimes cardiac arrhythmias.

Saline unresponsive metabolic alkalosis occurs due to renal problems:

- **With high BP:** excess mineralocorticoid (exogenous or endogenous)
- **With normal BP:** severe low potassium, high calcium
Chapter 3

Mini-tutorial: The use of i.v. sodium bicarbonate in metabolic acidosis

\( \text{HCO}_3^- \) as sodium bicarbonate may be administered i.v. to raise blood pH in severe metabolic acidosis but this poses several problems. It increases the formation of \( \text{CO}_2 \) which passes readily into cells (unlike \( \text{HCO}_3^- \)) and this worsens intracellular acidosis. The oxygen-dissociation curve is shifted to the left by alkalosis leading to impaired oxygen delivery to the tissues. Sodium bicarbonate contains a significant sodium load and because 8.4% solution is hypertonic, the increase in plasma osmolality can lead to vasodilatation and hypotension. Tissue necrosis can result from extravasation from the cannula. Some patients with airway or ventilation problems may need mechanical ventilation to counter the increased \( \text{CO}_2 \) production caused by an infusion of sodium bicarbonate. Many of the causes of metabolic acidosis respond to restoration of intravascular volume and tissue perfusion with oxygen, i.v. fluids and treatment of the underlying cause. For these reasons, routine i.v. sodium bicarbonate is not used in a metabolic acidosis. It tends to be reserved for specific conditions, for example tricyclic poisoning (when it acts as an antidote), treatment of hyperkalaemia and some cases of renal failure. It may also be used in other situations, but only by experts: 8.4% sodium bicarbonate = 1 mmol/ml of sodium or bicarbonate.

- High-dose penicillin therapy
- Ingestion of exogenous alkali with a low glomerular filtration rate

A summary of the changes in pH, PaCO\(_2\) and standard bicarbonate in different acid–base disturbances is shown in Fig. 3.2.

Interpreting an arterial blood gas report

There are a few simple rules when looking at an arterial blood gas report:

- Always consider the clinical situation
- An abnormal pH indicates the primary acid–base problem
- The body never overcompensates
- Mixed acid–base disturbances are common in clinical practice.

Any test has to be interpreted only in the light of the clinical situation. A normal blood gas result might be reassuring, but not, for example, if the patient has severe asthma, where a ‘normal’ PaCO\(_2\) level would be extremely worrying. The body’s compensatory mechanisms only aim to bring the pH towards normal and never swing like a pendulum in the opposite direction. So a low pH with a high PaCO\(_2\) and high standard bicarbonate is always a respiratory acidosis and never an overcompensated metabolic alkalosis. These principles will be easily seen as you work through the case histories at the end of this chapter. Many doctors miss vital information when interpreting arterial blood gas reports because they do not use a systematic method of doing so.

There are five steps in interpreting an arterial blood gas report:

1. Look at the pH first
2. Look at the PaCO\(_2\) and the standard bicarbonate (or BE) to see whether this is a respiratory or a metabolic problem, or both
3 Check the appropriateness of any compensation. For example, in a metabolic acidosis you would expect the PaCO$_2$ to be low. If the PaCO$_2$ is normal this indicates a ‘hidden’ respiratory acidosis as well.
4 Calculate the anion gap if there is a metabolic acidosis.
5 Finally, look at the PaO$_2$ and compare it to the inspired oxygen concentration (more on this in Chapter 4).

**Why arterial blood gases are an important test in critical illness**

Arterial blood gas analysis can be performed quickly and gives the following useful information:
- A measure of oxygenation (PaO$_2$)
- A measure of ventilation (PaCO$_2$)
- A measure of perfusion (standard bicarbonate or BE).

In other words, a measure of A, B and C, which is why it is an extremely useful test in the management of a critically ill patient.

**Key points – acid–base balance**

- The body maintains a narrow pH range using buffers and then the excretory functions of the lungs and kidneys.
- Acid–base disturbances occur when there is a problem with ventilation, a problem with renal function, or an overwhelming acid or base load the body cannot handle.
- Use the five steps outlined above when interpreting an arterial blood gas report so that important information is not missed.
- Arterial blood gas analysis is an important test in critical illness.

**Self-assessment: case histories**

Normal values: pH 7.35–7.45, PaCO$_2$ 4.5–6.0 (35–46 mmHg), PaO$_2$ 11–14.5 kPa (83–108 mmHg), BE −2 to + 2, st bicarbonate 22–28 mmol/l.

1 A 65-year-old man with chronic obstructive pulmonary disease (COPD) comes to the emergency department with shortness of breath. His arterial
blood gases on air show: pH 7.29, PaCO₂ 8.5 kPa (65.3 mmHg), st bicarbonate 30.5 mmol/l, BE +4, PaO₂ 8.0 kPa (62 mmHg). What is the acid–base disturbance and what is your management?

2 A 60-year-old ex-miner with COPD is admitted with shortness of breath. His arterial blood gases on air show: pH 7.36, PaCO₂ 9.0 kPa (65.3 mmHg), st bicarbonate 35 mmol/l, BE +6, PaO₂ 6.0 kPa (46.1 mmHg). What is the acid–base disturbance and what is your management?

3 A 24-year-old man with epilepsy comes to hospital in tonic–clonic status epilepticus. He is given i.v. Lorazepam. Arterial blood gases on 101/min oxygen via reservoir bag mask show: pH 7.05, PaCO₂ 8.0 (61.5 mmHg), standard bicarbonate 16 mmol/l, BE –8, PaO₂ 15 kPa (115 mmHg). His other results are sodium 140 mmol/l, potassium 4 mmol/l and chloride 98 mmol/l. What is his acid–base status and why? What is your management?

4 A 44-year-old man comes to the emergency department with pleuritic chest pain and shortness of breath which he has had for a few days. A small pneumothorax is seen on the chest X-ray. His arterial blood gases on 101/min oxygen via simple face mask show: pH 7.44, PaCO₂ 3.0 (23 mmHg), standard bicarbonate 16 mmol/l, BE –8, PaO₂ 30.5 kPa (234.6 mmHg). Is there a problem with acid–base balance?

5 A patient is admitted to hospital with breathlessness and arterial blood gases on air show: pH 7.2, PaCO₂ 4.1 kPa (31.5 mmHg), st bicarbonate 36 mmol/l, BE +10, PaO₂ 7.8 kPa (60 mmHg). Can you explain this?

6 An 80-year-old woman is admitted with abdominal pain. Her vital signs are normal, apart from cool peripheries and a tachycardia. Her arterial blood gases on air show: pH 7.1, PaCO₂ 3.5 kPa (30 mmHg), st bicarbonate 8 mmol/l, BE –20, PaO₂ 12 kPa (92 mmHg). You review the clinical situation again – she has generalised tenderness in the abdomen but it is soft. Her blood glucose is 6.0 mmol/l (100 mg/dl), her creatinine and liver tests are normal. The chest X-ray is normal. There are reduced bowel sounds. The ECG shows atrial fibrillation. What is the reason for the acid–base disturbance? What is your management?

7 A 30-year-old woman who is 36 weeks pregnant has her arterial blood gases taken on air because of pleuritic chest pain. The results are as follows: pH 7.48, PaCO₂ 3.4 kPa (26 mmHg), st bicarbonate 19 mmol/l, BE –4, PaO₂ 14 kPa (108 mmHg). What do these blood gases show? Could they indicate a pulmonary embolism?

8 A 45-year-old woman with a history of peptic ulcer disease reports 6 days of persistent vomiting. On examination she has a BP of 100/60 mmHg and looks dehydrated and unwell. Her blood results are as follows: sodium 140 mmol/l, potassium 2.2 mmol/l, chloride 86 mmol/l, venous (actual) bicarbonate 40 mmol/l, urea 29 mmol/l (blood urea nitrogen (BUN) 80 mg/dl), pH 7.5, PaCO₂ 6.2 kPa (53 mmHg), PaO₂ 14 kPa (107 mmHg), urine pH 5.0, urine sodium 2 mmol/l, urine potassium 21 mmol/l and urine chloride 3 mmol/l. What is the acid–base disturbance? How would you treat this patient? Twenty-four hours after appropriate therapy the venous bicarbonate is 30 mmol/l
and the following urine values are obtained: pH 7.8, sodium 100 mmol/l, potassium 20 mmol/l and chloride 3 mmol/l. How do you account for the high urinary sodium but low urinary chloride concentration?

9 A 50-year-old man is recovering on a surgical ward 10 days after a total colectomy for bowel obstruction. He has type 1 diabetes and is on i.v. insulin. His ileostomy is working normally. His vital signs are: BP 150/70 mmHg, respiratory rate 16/min, SpO2 98% on air, urine output 1200 ml per day, temperature normal and he is well perfused. The surgical team are concerned about his persistently high potassium (which was noted pre-operatively as well) and metabolic acidosis. His blood results are: sodium 130 mmol/l, potassium 6.5 mmol/l, urea 14 mmol/l (BUN 39 mg/dl), creatinine 180 µmol/l (2.16 mg/dl), chloride 109 mmol/l, normal synacthen test and albumin. He is known to have diabetic nephropathy and is on Ramipril. His usual creatinine is 180 µmol/l. His arterial blood gases on air show: pH 7.31, PaCO2 4.0 kPa (27 mmHg), st bicarbonate 15 mmol/l, BE −8, PaO2 14 kPa (108 mmHg). The surgical team are wondering whether this persisting metabolic acidosis means that there is an intra-abdominal problem, although a recent abdominal CT scan was normal. What is your advice?

10 Match the clinical history with the appropriate arterial blood gas values:

<table>
<thead>
<tr>
<th>pH</th>
<th>PaCO2</th>
<th>St bicarbonate (mmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a 7.39</td>
<td>8.45 kPa (65 mmHg)</td>
<td>37</td>
</tr>
<tr>
<td>b 7.27</td>
<td>7.8 kPa (60 mmHg)</td>
<td>26</td>
</tr>
<tr>
<td>c 7.35</td>
<td>7.8 kPa (60 mmHg)</td>
<td>32</td>
</tr>
</tbody>
</table>

- A severely obese 24-year-old man
- A 56-year-old lady with COPD who has been started on a diuretic for peripheral oedema, resulting in a 3 kg weight loss
- A 14-year-old girl with a severe asthma attack.

**Self-assessment: discussion**

1 There is an acidaemia (low pH) due to a high PaCO2 – a respiratory acidosis. The standard bicarbonate is just above normal. The PaO2 is low. Management starts with assessment and treatment of airway, breathing and circulation (ABC). Medical treatment of an exacerbation of COPD includes controlled oxygen therapy, nebulised salbutamol, steroids, antibiotics if necessary, i.v. aminophylline in some cases and non-invasive ventilation if the respiratory acidosis does not resolve quickly [3].

2 There is a normal pH with a high PaCO2 (respiratory acidosis) and a high st bicarbonate (metabolic alkalosis). Which came first? The clinical history
and the low-ish pH point towards this being a respiratory acidosis, compensated for by a raise in st bicarbonate (renal compensation). This is a chronic or compensated respiratory acidosis. If the pH fell further due to a raise in PaCO₂, you could call this an ‘acute on chronic respiratory acidosis’ which would look like this: pH 7.17, PaCO₂ 14.6 kPa (109 mmHg), standard bicarbonate 39 mmol/l, BE +7.6, PaO₂ 6.0 kPa (46.1 mmHg). Management would be the same as for case number 1, but note that non-invasive ventilation is only indicated when the pH falls below 7.35 due to a rise in PaCO₂.

3 There is an acidaemia (low pH) due to a high PaCO₂ and a low st bicarbonate – a mixed respiratory and metabolic acidosis. The PaO₂ is low in relation to the inspired oxygen concentration. The high PaCO₂ is likely to be due to airway obstruction and the respiratory depressant effects of i.v. benzodiazepines. This can be deduced because there is such a large difference between the inspired oxygen concentration (FiO₂) and the PaO₂. Aspiration pneumonia is another possibility. Persistent tonic–clonic seizures cause a lactic acidosis because of anaerobic muscle metabolism. Management starts with assessment and treatment of ABC (followed by disability and examination/planning (DE)). A benzodiazepine aborts 80% seizures in status epilepticus. Lorazepam is the drug of choice because seizures are less likely to relapse compared with diazepam (55% at 24 h compared with 50% at 2 h). Additional therapy is then required to keep seizures away – 15 mg/kg i.v. phentoyin as a slow infusion with cardiac monitoring is the initial treatment. If this fails, consider other diagnoses, further phentoyin and sedation with propofol or barbiturates on the ICU [4].

4 There is a normal pH with a low PaCO₂ (respiratory alkalosis) and a low st bicarbonate (metabolic acidosis). Which came first? The history and the high-ish pH point towards this being a respiratory alkalosis, compensated for by a fall in st bicarbonate. This is a compensated respiratory alkalosis. If you saw a similar arterial blood gas in an unwell diabetic, it could be an early (compensated) diabetic ketoacidosis.

5 As you may have guessed, this is an impossible blood gas – the answer is laboratory error!

6 There is an acidaemia (low pH) due to a very low st bicarbonate (metabolic acidosis). The PaCO₂ is appropriately low, although it should be lower than this – approximately 2.5 kPa, possibly indicating that she is tiring. The anion gap is not given. The PaO₂ is normal. The presence of atrial fibrillation is a clue to the diagnosis of ischaemic bowel. Intra-abdominal catastrophes are associated with a metabolic acidosis. This case illustrates that an ‘acute abdomen’ is often soft in the elderly. They commonly show few signs of an inflammatory response because of their less active immune system. Management starts with assessment and treatment of ABC followed by DE – call the surgeon.

7 There is a high pH (alkalaemia) due to a low PaCO₂ (respiratory alkalosis). The st bicarbonate is just below normal. The PaO₂ is normal. A respiratory
alkalosis is a normal finding in advanced pregnancy [5]. The alveolar–arterial (A-a) gradient is not affected by pregnancy and is normal in this case (see Chapter 4). Arterial blood gases can be normal in peripheral pulmonary emboli and therefore do not add to the management of this case.

There is a high pH (alkalaemia) due to a high bicarbonate (metabolic alkalosis). The PaCO₂ is just above normal. The PaO₂ is normal, assuming she is breathing room air. The potassium and chloride levels are both low. This is the hypokalaemic hypochloraemic metabolic alkalosis seen in prolonged vomiting due to gastric outflow obstruction. The physical findings and low urinary chloride point towards volume depletion. The patient requires i.v. saline (sodium chloride) with potassium. During therapy, volume expansion reduces the need for sodium reabsorption, hence the high levels in the urine. The discrepancy between urinary sodium and chloride is primarily due to urinary bicarbonate excretion. Further saline replacement is necessary for as long as the low urinary chloride persists, since it indicates ongoing chloride and volume depletion.

There is a low pH (acidaemia) due to a low st bicarbonate – a metabolic acidosis. The PaCO₂ is appropriately low. The anion gap may be calculated as $(130 + 6.5) - (12 + 109) = 15.5$ mmol/l, which is normal. The PaO₂ is normal. Common causes of a normal anion gap metabolic acidosis include renal tubular acidosis, diarrhoea, fistula or ileostomy and acetazolomide therapy. In this case, excessive gastrointestinal losses and acetazolomide can be excluded, which leaves a possible renal cause. Renal tubular acidosis is a collection of disorders in which the kidneys either cannot excrete H⁺ ions or generate bicarbonate. Only one of the renal tubular acids is associated with a high serum potassium – type 4, or hyporeninaemic hypoaldosteronism, found in patients with diabetic or hypertensive nephropathy (as in this case) and exacerbated by angiotensin converting enzyme inhibitors, aldosterone blockers, for example spironolactone and non-steroidal anti-inflammatory drugs. The metabolic acidosis seen in this condition is usually mild, with the st bicarbonate concentration remaining above 15 mmol/l. Treatment usually consists of dietary restriction of potassium and medication, for example oral furosemide.

Severe obesity suggests chronic hypercapnia (c). COPD and diuretic therapy suggest chronic hypercapnia with a superimposed metabolic alkalosis (a). A severe asthma attack suggests an acute respiratory acidosis (b).
**Appendix: Checking the consistency of arterial blood gas data**

H⁺ ions concentration is sometimes used instead of pH. A simple conversion between pH 7.2 and 7.5 is that \([H^+] = 80 \text{ minus the two digits after the decimal point. So if the pH is 7.35, then } [H^+] = 80 - 35 = 45 \text{ nmol/l (see Fig. 3.3).}

Earlier in this chapter, Box 3.1 on the Henderson–Hasselbach equation explained that pH is proportional to \([\text{HCO}_3^-]/\text{PaCO}_2\). Another way of writing this is as follows:

\[
[H^+] = Ka \times \frac{\text{PaCO}_2}{\text{HCO}_3^-}
\]

where \(K_a\) is the dissociation constant

\[
or [H^+] = 181 \times \frac{\text{PaCO}_2}{\text{HCO}_3^-} \quad \text{in kPa (or 24 \times \text{PaCO}_2 \text{ in mmHg})}
\]

The following arterial blood gas analysis: pH 7.25, PaCO₂ 4.5 kPa (35 mmHg), st bicarbonate 14.8 mmol/l, PaO₂ 8.0 kPa (61 mmHg) shows a metabolic acidosis. A pH of 7.25 \([H^+]\) of 55 nmol/l. Do the figures add up?

\[
181 \times \frac{4.5}{14.8} = 55
\]

Yes, a PaCO₂ of 4.5 kPa with a st bicarbonate of 14.8 would give a \([H^+]\) of 55 nmol/l. You may find this simple calculation useful when checking for laboratory error, or making up arterial blood gases for teaching material.

<table>
<thead>
<tr>
<th>pH</th>
<th>([H^+]) (nmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>26</td>
</tr>
<tr>
<td>7.5</td>
<td>32</td>
</tr>
<tr>
<td>7.4</td>
<td>40</td>
</tr>
<tr>
<td>7.3</td>
<td>50</td>
</tr>
<tr>
<td>7.2</td>
<td>63</td>
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<tr>
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<td>80</td>
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<tr>
<td>7.0</td>
<td>100</td>
</tr>
<tr>
<td>6.9</td>
<td>125</td>
</tr>
<tr>
<td>6.8</td>
<td>160</td>
</tr>
</tbody>
</table>

**Figure 3.3** pH and equivalent \([H^+]\).
References


Further resource