CHAPTER 2
Oxygen therapy

By the end of this chapter you will be able to:
•Prescribe oxygen therapy
•Understand the different devices used to deliver oxygen
•Understand the reasons why PaCO₂ rises
•Know the limitations of pulse oximetry
•Understand the principle of oxygen delivery
•Apply this to your clinical practice

Myths about oxygen
Oxygen was described by Joseph Priestley in 1777 and has become one of the most commonly used drugs in medical practice. Yet oxygen therapy is often described inaccurately, prescribed variably and understood little. In 2000 we carried out two surveys of oxygen therapy. The first looked at oxygen prescriptions for post-operative patients in a large district general hospital in the UK. It found that there were several dozen ways used to prescribe oxygen and that the prescriptions were rarely followed. The second asked 50 qualified medical and nursing staff working in acute areas about oxygen masks and the concentration of oxygen delivered by each [1]. They were also asked which mask was most appropriate for a range of clinical situations. The answers revealed that many staff could not name the different types of oxygen mask, the difference between oxygen flow and concentration was poorly understood, one third chose a 28% Venturi mask for an unwell asthmatic and very few staff understood that PaCO₂ rises most commonly due to reasons that have nothing to do with oxygen therapy.

Misunderstanding of oxygen therapy is widespread and the result is that many patients are treated suboptimally. Yet oxygen is a drug with a correct concentration and side effects.

Hypoxaemia and hypoxia
Hypoxaemia is defined as the reduction below normal levels of oxygen in arterial blood – a PaO₂ of less than 8.0 kPa (60 mmHg) or oxygen saturations less than 93%. The normal range for arterial blood oxygen is 11–14 kPa (85–105 mmHg) which reduces in old age. Hypoxia is the reduction below
normal levels of oxygen in the tissues and leads to organ damage. Cyanosis is an unreliable indicator of hypoxaemia, since its presence also depends on the haemoglobin concentration.

The main causes of hypoxaemia are as follows:

- Hypoventilation
- Ventilation–perfusion (V/Q) mismatch
- Intrapulmonary shunt.

These are discussed further in Chapter 4. Tissue hypoxia can also be caused by circulation abnormalities and impaired oxygen utilisation, for example in severe sepsis (discussed further in Chapter 6).

Symptoms and signs of hypoxaemia include:

- Cyanosis
- Restlessness
- Palpitations
- Sweating
- Confusion
- Headache
- Hypertension then hypotension
- Reduced conscious level.

The goal of oxygen therapy is to correct alveolar and tissue hypoxia, aiming for a PaO₂ of at least 8.0 kPa (60 mmHg) or oxygen saturations of at least 93%. Aiming for oxygen saturations of 100% is usually unnecessary and wasteful.

**Oxygen therapy**

There are very few published guidelines on oxygen therapy for acutely ill patients. The American Association for Respiratory Care has published the following indications for oxygen therapy [2]:

- Hypoxaemia (PaO₂ less than 8.0 kPa/60 mmHg, or saturations less than 93%)
- An acute situation where hypoxaemia is suspected
- Severe trauma
- Acute myocardial infarction
- During surgery.

However, oxygen therapy is also indicated in the peri-operative period, for respiratory distress, shock, severe sepsis, carbon monoxide (CO) poisoning, severe anaemia and when drugs are used which reduce ventilation (e.g. opioids). Post-operative oxygen therapy reduces cardiac ischaemic events, and high-concentration oxygen therapy has been shown to reduce post-operative nausea and vomiting in certain patients and wound infections after colorectal surgery.

Oxygen masks are divided into two groups, depending on whether they deliver a proportion of, or the entire ventilatory requirement (Fig. 2.1):

1. **Low flow masks**: Nasal cannulae, Hudson (or MC) masks and reservoir bag masks.
2. **High flow masks**: Venturi masks.
Any oxygen delivery system can also be humidified. In common use in the UK is a humidified oxygen circuit which uses an adjustable Venturi valve.

**Nasal cannulae**
Nasal cannulae are commonly used because they are convenient and comfortable. Nasal catheters (a single tube inserted into a nostril with a sponge) are also sometimes used. The oxygen flow rate does not usually exceed 4 l/min.

Figure 2.1 Different oxygen masks. (a) Nasal cannulae, (b) Hudson or MC mask, (c) Mask with a reservoir bag and (d) Venturi mask. Reproduced with permission from Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.
because this tends to be poorly tolerated by patients. If you look closely at the packaging of nasal cannulae, you will read that 2 l/min of oxygen via nasal cannulae delivers 28% oxygen. This statement makes many assumptions about the patient’s pulmonary physiology. In fact, the concentration of oxygen delivered by nasal cannulae is variable both between patients and in the same patient at different times. The concentration is affected by factors such as the size of the anatomical reservoir and the peak inspiratory flow rate.

If you take a deep breath in, you will inhale approximately 1 l of air in a second. This is equivalent to an inspiratory flow rate of 60 l/min. The inspiratory flow rate varies throughout the respiratory cycle, hence there is also a peak inspiratory flow rate. Normal peak inspiratory flow rate is 40–60 l/min. But imagine for a moment that the inspiratory flow rate is constant. If a person has an inspiratory flow rate of 30 l/min and is given 2 l/min oxygen via nasal cannulae, he will inhale 2 l/min of pure oxygen and 28 l/min of air. If that same person changes his pattern of breathing so that the inspiratory flow rate rises to 60 l/min, the person will now inhale 2 l/min of pure oxygen and 58 l/min of air. In other words, a person with a higher inspiratory flow rate inhales proportionately less oxygen, and a person with a lower inspiratory flow rate inhales proportionately more oxygen. All low flow masks have this characteristic and therefore deliver a variable concentration of oxygen.

The theoretical oxygen concentrations for nasal cannulae at various flow rates are given in Fig. 2.2. These concentrations are a rough guide and apply to an average, healthy person. But because nasal cannulae in fact deliver a variable concentration of oxygen, there are several case reports on the ‘dangers of low flow oxygen’ during exacerbations of chronic obstructive pulmonary disease (COPD) [3] where low inspiratory flow rates can occur (and therefore higher oxygen concentrations).

### Hudson or MC masks

Hudson or MC (named after Mary Catterall but also referred to as ‘medium concentration’) masks are also sometimes called ‘simple face masks’. They are said to deliver around 50% oxygen when set to 10–15 l/min. The mask provides an additional 100–200 ml oxygen reservoir and that is why a higher
concentration of oxygen is delivered compared with nasal cannulae. However, just like nasal cannulae, the concentration of oxygen delivered varies depending on the peak inspiratory flow rate as well as the fit of the mask. Importantly (and usually not known), significant rebreathing of CO₂ can occur if the oxygen flow rate is set to less than 5 l/min because exhaled air may not be adequately flushed from the mask. Nasal cannulae should be used if less than 5 l/min of low flow oxygen is required.

Reservoir bag masks
Reservoir bag masks are similar in design to Hudson masks, with the addition of a 600–1000-ml reservoir bag which increases the oxygen concentration still further. Reservoir bag masks are said to deliver around 80% oxygen at 10–15 l/min, but again this varies depending on the peak inspiratory flow rate as well as the fit of the mask. There are two types of reservoir bag mask: partial rebreathe masks and non-rebreathe masks. Partial rebreathe masks conserve oxygen supplies - useful if travelling with a cylinder. The first one-third of the patient’s exhaled gas fills the reservoir bag, but as this is primarily from the anatomical deadspace, it contains little CO₂. The patient then inspires a mixture of exhaled gas and fresh gas (mainly oxygen). Non-rebreathe masks are so called because exhaled air exits the side of the mask through one-way valves and is prevented from entering the reservoir bag by another one-way valve. The patient therefore only inspires fresh gas (mainly oxygen). With both types of reservoir bag masks, the reservoir should be filled with oxygen before the mask is placed on the patient and the bag should not deflate by more than two-thirds with each breath in order to be effective. If the oxygen flow rate and oxygen reservoir are insufficient to meet the inspiratory demands of a patient with a particularly high inspiratory flow rate, the bag may collapse and the patient’s oxygenation could be compromised. To prevent this, reservoir bag masks must be used with a minimum of 10 l/min of oxygen, and some are fitted with a spring-loaded tension valve which will open and allow entrainment of room air if necessary.

It is impossible for a patient to receive 100% oxygen via any mask for the simple reason that there is no airtight seal between mask and patient. Entrained air is always inspired as well.

Nasal cannulae, Hudson or MC masks, and reservoir bag masks all deliver a variable concentration of oxygen. They are all called low flow masks because the highest gas flow from the mask is 15 l/min, whereas a patient’s inspiratory flow rate can be much higher. It is important to realise that low flow does not necessarily mean low concentration.

Venturi masks
Venturi masks, on the other hand, are high flow masks. The Venturi valve utilises the Bernoulli principle and has the effect of increasing the gas flow to above the patient’s peak inspiratory flow rate (which is why these masks make more noise). A changing inspiratory pattern does not affect the oxygen
concentration delivered, because the gas flow is high enough to meet the patient’s peak inspiratory demands.

Bernoulli observed that fluid velocity increases at a constriction. This is what happens when you put your thumb over the end of a garden hose. If you were to look down a Venturi valve, you would observe a small hole. Oxygen is forced through this short constriction and the sudden subsequent increase in area creates a pressure gradient which increases velocity and entrains room air (see Fig. 2.3). At the patient’s face there is a constant air–oxygen mixture which flows at a rate higher than the normal peak inspiratory flow rate. So changes in the pattern of breathing do not affect the oxygen concentration. There are two types of Venturi systems: colour-coded valve masks and a variable model. With colour-coded valve masks (labelled 24%, 28%, 35%, 40% and 60%), each is designed to deliver a fixed percentage of oxygen when set to the appropriate flow rate. To change the oxygen concentration, both the valve and flow have to be changed. The size of the orifice and the oxygen flow rate are different for each type of valve, because they have been calculated accordingly. The variable model is most commonly encountered in the UK with humidified oxygen circuits. The orifice is adjustable and the oxygen flow rate is set depending on what oxygen concentration is desired.

![Figure 2.3](image)

**Figure 2.3** A 28% Venturi mask. Bernoulli’s equation for incompressible flow states that $1/2p v^2 + P = \text{constant}$ (where $p$ is density) so if the pressure ($P$) of a gas falls, it gains velocity ($v$). When gas moves through the Venturi valve there is a sudden drop due to the increase in area. The velocity or flow of gas increases according to the above equation and entrains air as a result.
Venturi masks are the first choice in patients who require controlled oxygen therapy. The concentration of inspired oxygen is determined by the mask rather than the characteristics of the patient. Increasing the oxygen flow rate will increase total gas flow, but not the inspired oxygen concentration. However, with inspired oxygen concentrations of over 40%, the Venturi system may still not have enough total flow to meet high inspiratory demands. Fig. 2.4 shows the flow rates for various Venturi masks and Fig. 2.5 shows the effect of lower total flow rates in patients with high inspiratory demands.

<table>
<thead>
<tr>
<th>Venturi valve colour</th>
<th>Inspired oxygen concentration (%)</th>
<th>Oxygen flow (l/min)</th>
<th>Total gas flow (l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>24</td>
<td>2–4</td>
<td>51–102</td>
</tr>
<tr>
<td>White</td>
<td>28</td>
<td>4–6</td>
<td>44–67</td>
</tr>
<tr>
<td>Yellow</td>
<td>35</td>
<td>8–10</td>
<td>45–65</td>
</tr>
<tr>
<td>Red</td>
<td>40</td>
<td>10–12</td>
<td>41–50</td>
</tr>
<tr>
<td>Green</td>
<td>60</td>
<td>12–15</td>
<td>24–30</td>
</tr>
<tr>
<td>Humidified circuit</td>
<td>85</td>
<td>12–15</td>
<td>15–20</td>
</tr>
</tbody>
</table>

**Figure 2.4** Venturi mask flow rates. Data provided by Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.

- Venturi humidified oxygen circuit set to 85% with an oxygen flow rate of 15 l/min (total gas flow 20 l/min).
- The curve shows a patient’s inspiratory flow pattern with a peak inspiratory flow rate of 40 l/min. The total gas flow is only 20 l/min, so for part of the inspiratory cycle, the patient is breathing mainly air. This reduces the overall inspired oxygen concentration to around 60%.

**Figure 2.5** Lower total flow rates in patients with high inspiratory demands. Data provided by Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.
Humidified oxygen

Normally, inspired air is warmed and humidified to almost 90% by the nasopharynx. Administering dry oxygen lowers the water content of inspired air, even more so if an artificial airway bypasses the nasopharynx. This can result in ciliary dysfunction, impaired mucous transport, retention of secretions, atelectasis, and even bacterial infiltration of the pulmonary mucosa and pneumonia. Humidified oxygen is given to avoid this, and is particularly important when prolonged high-concentration oxygen is administered and in pneumonia or post-operative respiratory failure where the expectoration of secretions is important.

In summary, flow is not the same as concentration! Low flow masks can deliver high concentrations of oxygen and high flow masks can deliver low concentrations of oxygen. Therefore, the terms ‘high concentration’ and ‘low concentration’ should be used when discussing oxygen therapy. Furthermore, when giving instructions or prescribing oxygen therapy, two parts are required: the type of mask and the flow rate. You cannot simply say ‘28%’ as this is meaningless – one person might assume this means a 28% Venturi mask, and another may assume this means 2 l/min via nasal cannulae. If the patient has an exacerbation of COPD, this difference could be important.

Why are there so many different types of oxygen mask? Nasal cannulae are convenient and comfortable. Patients can easily speak, eat and drink wearing nasal cannulae. Reservoir bag masks deliver the highest concentrations of oxygen and should always be available in acute areas. A fixed concentration of oxygen is important for many patients, as is humidified oxygen. Since Venturi masks deliver a range of oxygen concentrations from 24% to 60%, some hospital departments in the UK choose not to stock Hudson (MC) masks as well. Fig. 2.6 shows which mask is appropriate for different clinical situations and Fig. 2.7 shows a simple guide to oxygen therapy. Oxygen therapy should be goal directed. The right patient should receive the right amount of oxygen for the right length of time.

<table>
<thead>
<tr>
<th>Oxygen mask</th>
<th>Clinical situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nasal cannulae (2–4 l/min)</td>
<td>Patients with otherwise normal vital signs (e.g. post-operative, slightly low SpO₂, long-term oxygen therapy).</td>
</tr>
<tr>
<td>Hudson masks (more than 5 l/min)</td>
<td>Higher concentrations required and controlled oxygen not necessary (e.g. severe asthma, acute left ventricular failure, pneumonia, trauma, severe sepsis).</td>
</tr>
<tr>
<td>Hudson masks (more than 10 l/min)</td>
<td>Higher concentrations required and controlled oxygen not necessary (e.g. severe asthma, acute left ventricular failure, pneumonia, trauma, severe sepsis).</td>
</tr>
<tr>
<td>Venturi masks</td>
<td>Controlled oxygen therapy required (e.g. patients with exacerbation of COPD).</td>
</tr>
</tbody>
</table>

Figure 2.6 Which mask for which patient?
Can oxygen therapy be harmful?

Hyperoxaemia can sometimes have adverse effects. Prolonged exposure to high concentrations of oxygen (above 50%) can lead to atelectasis and acute lung injury, usually in an ICU setting. Absorption atelectasis occurs as nitrogen is washed out of the alveoli and oxygen is readily absorbed into the bloodstream, leaving the alveoli to collapse. Acute lung injury is thought to be due to oxygen free radicals. Hyperoxaemia can increase systemic vascular resistance which may be a disadvantage in some patients. Oxygen is also combustible. There is also a group of patients with chronic respiratory failure who may develop hypercapnia when given high concentrations of oxygen, a fact which is usually emphasised in undergraduate medical teaching.

But!!!

Hypoxaemia kills. There have been cases of negligence in which doctors have withheld oxygen therapy from acutely ill patients due to an unfounded fear of exacerbating hypercapnia. The next section will discuss in detail the causes of hypercapnia with special reference to oxygen therapy, and the role of acute oxygen therapy in patients with chronic respiratory failure, particularly COPD.
Hypercapnia and oxygen therapy

From a physiological point of view, PaCO₂ rises for the following reasons:

- Alveolar hypoventilation (alveolar ventilation is the portion of ventilation which takes part in gas exchange; it is not the same as a reduced respiratory rate).
- V/Q mismatch. PaO₂ falls and PaCO₂ rises when blood flow is increased to poorly ventilated areas of lung and the patient cannot compensate by an overall increase in alveolar ventilation.
- Increased CO₂ production (e.g. severe sepsis, malignant hyperthermia, bicarbonate infusion) where the patient cannot compensate by an overall increase in alveolar ventilation.
- Increased inspired PaCO₂ (e.g. breathing into a paper bag).

Fig. 2.8 shows how respiratory muscle load and respiratory muscle strength can become affected by disease and an imbalance leads to alveolar hypoventilation and hypercapnia. Respiratory muscle load is increased by increased resistance (e.g. upper or lower airway obstruction), reduced compliance (e.g. infection, oedema, rib fractures or obesity) and increased respiratory rate. Respiratory muscle strength can be reduced by a problem in any part of the neurorespiratory pathway: motor neurone disease, Guillain–Barré syndrome, myasthenia gravis or electrolyte abnormalities (low potassium, magnesium, phosphate or calcium). It is important to realise that alveolar hypoventilation usually occurs with a high (but ineffective) respiratory rate, as opposed to total hypoventilation (a reduced respiratory rate) which is usually caused by drug overdose.

A problem with ventilation is the most common cause of hypercapnia among hospital in-patients. Examples include the overdose patient with airway obstruction, the ‘tired’ asthmatic, the morbidly obese patient with pneumonia, the patient with post-operative respiratory failure on an opioid infusion, the trauma patient with rib fractures and pulmonary contusions, the pancreatitis patient with acute respiratory distress syndrome, the patient with acute pulmonary oedema on the coronary care unit and so on.

In other words, oxygen therapy is an uncommon cause of hypercapnia.

There are many conditions in which chronic hypercapnia occurs: severe chest wall deformity, morbid obesity and neurological conditions causing

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**Figure 2.8** The balance between respiratory muscle load and strength.
muscle weakness, for example. The reasons for chronic hypercapnia in COPD are not really known, but are thought to include a low chemical drive for breathing, genetic factors and an acquired loss of drive due to adaptation to increased work of breathing. Chronic hypercapnia in COPD tends to occur when the forced expiratory volume (FEV$_1$) is less than 1 l.

For the purposes of explanation here, the term ‘CO$_2$ retention’ will be used to describe acute hypercapnia when patients with chronic respiratory failure are given high-concentration (or uncontrolled) oxygen therapy. ‘Ventilatory failure’ will be used to describe acute hypercapnia due to other causes.

**CO$_2$ retention**

In 1949 a case was described of a man with emphysema who lapsed into a coma after receiving oxygen therapy but rapidly recovered after the oxygen was removed [4]. In 1954 a decrease in ventilation was observed in 26 out of 35 patients with COPD given oxygen therapy, with a rise in PaCO$_2$ and a fall in pH. No patient with a normal baseline PaO$_2$ showed these changes [5]. In a further study it was showed that stopping and starting oxygen therapy led to a fall and rise in PaCO$_2$, respectively [6]. These early experiments led to the concept of ‘hypoxic drive’, proposed by Campbell [7], which is taught in medical schools today. The teaching goes like this: changes in PaCO$_2$ is one of the main controls of ventilation in normal people. In patients with a chronically high PaCO$_2$ the chemoreceptors in the brain become blunted and the patient depends on hypoxaemia to stimulate ventilation, something which normally occurs only at altitude or during illness. If these patients are given too much oxygen, their ‘hypoxic drive’ is abolished, breathing will slow and PaCO$_2$ will rise as a result, causing CO$_2$ narcosis and eventually apnoea.

Unfortunately, hypoxic drive is not responsible for the rise in PaCO$_2$ seen when patients with chronic respiratory failure are given uncontrolled oxygen therapy. Subsequent studies have questioned this theory and it is now thought that changes in V/Q are more important in the aetiology of CO$_2$ retention. Hypoxic vasoconstriction is a normal physiological mechanism in the lungs. When oxygen therapy is given to patients with chronic hypoxemia, this is reversed leading to changes in V/Q. PaCO$_2$ rises because more CO$_2$-containing blood is delivered to less well-ventilated areas of lung. In a person with a normal chemical drive for breathing, this would be compensated for by an overall increase in alveolar ventilation. But if the chemical drive for breathing is impaired (as in some patients with COPD), or there are mechanical limitations to increasing ventilation, or fatigue, this cannot occur. In other words, the combination of changes in V/Q plus the inability to compensate is why CO$_2$ retention occurs. Studies have failed to show a reduction in minute ventilation to account for this phenomenon, although it is possible it may contribute in some way [8,9].

Which patients are at risk of CO$_2$ retention? The answer is patients with chronic respiratory failure. It is not the label ‘COPD’, but the presence of chronic respiratory failure, which occurs in other diseases as well, that is important. Some
Oxygen therapy

Patients with COPD are fairly physiologically normal. This may explain the studies which show no significant change in PaCO₂ when patients with an exacerbation of COPD were given high-concentration oxygen therapy. In one study, patients with a PaO₂ of less than 6.6 kPa (50 mmHg) and a PaCO₂ of more than 6.6 kPa (50 mmHg) were randomised to receive oxygen therapy either to get the PaO₂ just above 6.6 kPa or above 9 kPa (70 mmHg). There was no significant difference between the two groups in terms of mortality, need for ventilation, duration of hospital stay, PaCO₂ or pH despite a significant difference in PaO₂. There was a trend towards improved outcome in the higher oxygen group [10].

Half of admissions with an acute exacerbation of COPD have reversible hypercapnia [11,12]. In other words, these people have acute but not chronic respiratory failure. Non-invasive ventilation has been shown to be a very successful treatment for acute respiratory failure (or acute on chronic respiratory failure) in COPD, leading to a reduction in mortality and length of hospital stay [13]. How can you tell if a patient with COPD has a high PaCO₂ because of oxygen therapy (CO₂ retention) or because they are sick (ventilatory failure), and does it matter, since the treatment is essentially the same: controlled oxygen therapy titrated to arterial blood gases, medical therapy and ventilation if needed?

Fig. 2.9 is a simplified guide to the clinical differences between CO₂ retainers and patients with ventilatory failure and COPD. Of course, many patients

<table>
<thead>
<tr>
<th>Likely CO₂ retention</th>
<th>Likely ventilatory failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usually severely limited by breathlessness</td>
<td>Not usually limited by breathlessness</td>
</tr>
<tr>
<td>Cor pulmonale or polycythaemia present</td>
<td>No signs of chronic hypoxaemia</td>
</tr>
<tr>
<td>FEV₁ less than 1 l</td>
<td>FEV₁ good</td>
</tr>
<tr>
<td>On home nebulisers and/or home oxygen</td>
<td>Inhalers only</td>
</tr>
<tr>
<td>Abnormal blood gases when well</td>
<td>Normal blood gases when well</td>
</tr>
<tr>
<td>Admission blood gases show pH and st bicarbonate/BE consistent with chronic hypercapnia</td>
<td>Admission blood gases show pH and st bicarbonate/BE consistent with critical illness</td>
</tr>
<tr>
<td>Vital signs and oxygen saturations not very different to normal</td>
<td>Critically ill</td>
</tr>
<tr>
<td>Reasonable air entry</td>
<td>Silent chest or feeble chest movements</td>
</tr>
<tr>
<td></td>
<td>Dubious diagnosis of COPD</td>
</tr>
<tr>
<td></td>
<td>Chest X-ray shows pulmonary oedema or severe pneumonia</td>
</tr>
</tbody>
</table>

**Figure 2.9** CO₂ retention due to oxygen therapy vs ventilatory failure in patients with COPD.
will fall in between these two extremes (in which case a pragmatic approach is required), but it is nevertheless a useful guide, especially when teaching.

One in five patients with COPD admitted to hospital has a respiratory acidosis. The more severe the acidosis, the greater the mortality. Some of these acidoses may be caused by uncontrolled oxygen therapy, since a proportion disappears quickly after arrival in hospital [14], although this may also be due to treatment with bronchodilators. Recent UK National Institute for Clinical Excellence (NICE) guidelines recommend using Venturi masks in conjunction with pulse oximetry for exacerbations of COPD, increasing or reducing the oxygen to maintain saturations of 90–93%, until further information can be gained from arterial blood gases [15]. Despite such guidelines, oxygen therapy in COPD continues to cause controversy. This may be because patients with COPD constitute a physiologically diverse group and so there can be no ‘rules’. For example, in 2002, the journal *Clinical Medicine* published an audit of oxygen therapy in acute exacerbations of COPD [16]. One hundred and one admissions were analysed and 57% of patients received more than 28% oxygen on their way to hospital. The median duration from ambulance to first arterial blood gas was 1 h. Half of the patients identified their illness incorrectly as ‘asthma’ to the ambulance crew. Controversially, the audit found that in-hospital mortality was greater in those patients who received more than 28% oxygen and postulated that there was a causal relationship. The publication of this article was followed by the publication of a strongly worded letter by two eminent critical care physicians and it is worth reading in full [17]. They strongly disagreed with the assumptions behind the article, and among other things, pointed out that nearly all studies involving patients with an acute exacerbation of COPD ignore the base deficit in their comparisons of outcome and mention only pH, PaCO₂ and PaO₂. Since the base deficit is known to correlate strongly with mortality [18], outcome studies which ignore it are meaningless. They finished by saying, ‘we frequently attend A&E departments to treat [patients with an exacerbation of COPD] and routinely use high-concentration oxygen, despite a high PaCO₂, in conjunction with mechanical ventilation (invasive or non-invasive) because their major problem is fatigue, often compounded by atelectasis due to shallow respiratory efforts, weak cough and sputum retention, rather than the semi-mythical loss of hypoxic drive. To allow them to remain hypoxaemic (i.e. below their normal baseline) and thus struggle and tire further is contrary to all the precepts underpinning ABC resuscitation and good clinical practice. Remarkably, our patients often do very well. As a simple rule of thumb, hypoxic drive is a non-issue in tachypnoeic patients’.

The answer to the question ‘How much oxygen should be given in an exacerbation of COPD?’ is therefore: enough, monitored closely and in conjunction with other treatments.

To summarise:

- The most common cause of hypercapnia for hospital in-patients is acute illness causing ventilatory failure. This has nothing to do with oxygen therapy – treat the cause.
• In patients with chronic respiratory failure, start with a 28% Venturi mask and titrate oxygen therapy to arterial blood gases (see Fig. 2.7).
• Controlled oxygen therapy, medical treatment and mechanical ventilation are used to treat acute respiratory acidosis (low pH due to a high PaCO₂) in an exacerbation of COPD.

**Pulse oximetry**

Oximetry works on the principle that light is absorbed by a solution, and the degree of absorption is related to the molar concentration of that solution (Fig. 2.10). The Lambert and Beer laws describe this. Oxyhaemoglobin (HbO₂) and de-oxyhaemoglobin (Hb) have different absorbencies at certain wavelengths of light (660 and 940 nm). There are two ways to measure haemoglobin oxygen saturation using oximetry: by a co-oximeter or a pulse oximeter. A co-oximeter haemolyses blood and is a component of most blood gas machines. It measures SaO₂. A pulse oximeter consists of a peripheral probe and a central processing and
display unit. It measures SpO₂. Two light emitting diodes (LEDs) in the probe of a pulse oximeter transilluminate separate pulses of light in the red and infrared spectra, and the absorbance is measured by a photodiode on the other side, enabling the concentration of HbO₂ and Hb, and therefore haemoglobin saturation to be calculated. This is the ‘functional saturation’ as further calculations are then done to account for minor haemoglobin species. The probe is able to correct for ambient light. As blood flow is pulsatile, the transilluminated signal consists of an ‘AC’ component as well as a ‘DC’ component (which represents the light absorbed by tissues and resting blood). Although the AC component is a small proportion of the total signal, it is a major determinant of accuracy, which explains why pulse oximeters are inaccurate in low perfusion states.

Oximeters are calibrated by the manufacturers using data that was originally obtained by human volunteers. SpO₂ was measured while the volunteers inspired various oxygen concentrations. Due to this, they are only accurate between 80% and 100% saturation, as it was unethical to calibrate oximeters below this point.

Oxygen saturation indirectly relates to arterial oxygen content (PaO₂) through the oxygen dissociation curve. Remembering this indirect relationship is

The oxygen dissociation curve falls sharply after saturation of 93% (8.0 kPa). SpO₂ of 93% or less is abnormal and requires assessment.

- The curve is shifted to the right in fever, raised 2,3-diphosphoglycerate (2,3-DPG) and acidosis (the shift caused by pH is called the Bohr effect). This means P₅₀ increases and higher pulmonary capillary saturations are required to saturate Hb, but there is enhanced delivery at the tissues.

- The curve is shifted to the left by hypothermia, reduced 2,3-DPG, alkalosis and the presence of foetal Hb. This means P₅₀ reduces and lower pulmonary capillary saturations are required to saturate Hb, but lower tissue capillary PaO₂ is required before oxygen is delivered.

Figure 2.11 The oxygen dissociation curve.
important, because SpO2 is affected by several internal factors (see Fig. 2.11) as well as external factors, listed below. It is also important to remember that SpO2 is only a measure of oxygenation, not ventilation.

The technical limitations of pulse oximetry include the following:

- Motion artefact – excessive movement (e.g. in the back of an ambulance) interferes with the signal.
- External light from fluorescent lighting and poorly shielded probes also interferes with the signal.
- An ill-fitting probe may give spurious readings.
- Injectable dyes such as methylene blue can interfere with SpO2 readings for several hours.
- Dark nail polish may interfere with the signal.
- Anaemia – at a Hb of 8 g/dl the oxygen saturation is underestimated by 10–15%, especially at lower saturation levels.
- Vasoconstriction and poor tissue perfusion give low amplitude signals which increase error. Modern oximeters display ‘poor signal’ messages.
- Abnormal haemoglobins – methaemoglobin reduces SpO2 despite a normal PaO2, and carboxyhaemoglobin is not detected by pulse oximetry despite a low PaO2.

Dark skin has been studied and does not affect the accuracy of pulse oximetry.

**Oxygen delivery**

Tissues need oxygen to metabolise. Nearly all oxygen is carried to the tissues by haemoglobin. Each g/dl of haemoglobin carries 1.3 ml of oxygen when fully saturated. The oxygen content of blood can therefore be calculated as:

\[
\text{Hb (g/dl)} \times \text{oxygen saturation of Hb} = 1.3
\]

Haemoglobin is delivered to the tissues by the circulation. The amount of oxygen delivered per minute depends on the cardiac output. From this we derive the oxygen delivery equation:

\[
\text{Hb} (\times 10 \text{ to convert to litres}) \times \text{SaO}_2 \times 1.3 \times \text{CO(l/min)}
\]

Oxygen delivery is an important concept in intensive care medicine. In fact, the importance of oxygen delivery explains the emphasis on airway, breathing and circulation (ABC) in teaching acute care. Understanding that oxygen delivery depends on more than just oxygen therapy will help you optimise your patient’s condition. In the ICU, oxygen delivery is manipulated in high-tech ways. The following is a simple ward-based example: in a 70-kg man a normal Hb is 14 g/dl, normal SaO2 is 95% and normal cardiac output is 5 l/min. Oxygen delivery is therefore 14 × 0.95 × 1.3 × 10 × 5 = 864.5 ml O2/min. Imagine this patient now has severe pneumonia and is dehydrated. His SaO2 is 93% and he has a reduced cardiac output (4 l/min). His oxygen delivery is 14 × 0.93 × 1.3 × 10 × 4 = 677 ml O2/min. By increasing his oxygen so that his saturations are now 98% his oxygen delivery can be increased to
713 ml O₂/min, but if a fluid challenge is given to increase his cardiac output to normal (5 l/min), yet his oxygen is kept the same, his oxygen delivery can be increased to 846 ml O₂/ min. Oxygen delivery has been increased more by giving fluid than by giving oxygen.

The oxygen delivery equation also illustrates the relationship between SaO₂ and haemoglobin. An SaO₂ of 95% with severe anaemia is worse in terms of oxygen delivery than an SaO₂ of 80% with a haemoglobin of 15 g/dl, and this is why patients with chronic hypoxaemia develop polycythaemia.

**Key points: oxygen therapy**

- The goal of oxygen therapy is to correct alveolar and tissue hypoxia, aiming for a PaO₂ of at least 8.0 kPa (60 mmHg) or oxygen saturations of at least 93%.
- Oxygen masks are divided into two groups: low flow masks which deliver a variable concentration of oxygen (nasal cannulae, Hudson or MC masks and reservoir bag masks) and high flow Venturi masks which deliver a fixed concentration of oxygen.
- The most common cause of hypercapnia for hospital in-patients is ventilatory failure. This has nothing to do with oxygen therapy – treat the cause.
- Pulse oximetry is a measure of oxygenation, not ventilation.

**Self-assessment: case histories**

1. A 60-year-old woman arrives in the Emergency Department with breathlessness. She was given 12 l/min oxygen via simple face mask by the paramedics. She is on inhalers for COPD, is a smoker and has diabetes. She is clammy and has widespread crackles and wheeze in the lungs. The chest X-ray has an appearance consistent with severe left ventricular failure. Her blood gases are: pH 7.15, PaCO₂ 8.0 kPa (61.5 mmHg), PaO₂ 9.0 kPa (69.2 mmHg), st bicarbonate 20 mmol/l, base excess (BE) −6. The attending doctor has taken the oxygen mask off because of ‘CO₂ retention’ by the time you arrive. The oxygen saturations were 95% and are now 85%. Blood pressure is 180/70 mmHg. Comment on her oxygen therapy. What is your management?

2. A 50-year-old man arrives in the Medical Admissions Unit with breathlessness. He is an ex-miner, has COPD and is on inhalers at home. His blood gases on 28% oxygen show: pH 7.4, PaCO₂ 8.5 kPa (65.3 mmHg), PaO₂ 8.5 kPa (65.3 mmHg), st bicarbonate 38.4 mmol/l, BE +7. A colleague asks you if he needs non-invasive ventilation because of his hypercapnia. What is your reply?

3. A 40-year-old patient on the chemotherapy ward becomes unwell with breathlessness. The nurses report oxygen saturations of 75%. When you go to the patient, you find the other observations are as follows: pulse
31

130/min, blood pressure 70/40 mmHg, respiratory rate 40/min, patient confused. Blood gases on air show: pH 7.1, PaCO2 3.0 kPa (23 mmHg), PaO2 13 kPa (115 mmHg), st bicarbonate 6.8 mmol/l, BE −20. The chest is clear. A chest X-ray is taken and is normal. Can you explain the oxygen saturations and the breathlessness? What is your management?

4 A 50-year-old man is undergoing a urological procedure. As part of this, intravenous methylene blue is given. Shortly afterwards, the junior anaesthetist notices the patient’s oxygen saturations drop suddenly to 70%. All the equipment seems to be working normally. Worried that the patient has had some kind of embolism, he calls his senior. What is the explanation?

5 A 45-year-old man arrives unconscious in the Emergency Department. There is no history available apart from he was found collapsed in his car by passers-by. On examination he is unresponsive, pulse 90/min, blood pressure 130/60 mmHg, oxygen saturations 98% on 15 l/min oxygen via reservoir bag mask. His ECG shows widespread ST depression and his arterial blood gases show: pH 7.25, PaCO2 6.0 kPa (46 mmHg), PaO2 7.5 kPa (57.6 mmHg), st bicarbonate 19.4 mmol/l, BE −10. His full blood count is normal. What is the explanation for the discrepancy in the SpO2 and PaO2? What is your management?

6 A 25-year-old man with no past medical history was found on the floor at home having taken a mixed overdose of benzodiazepines and tricyclic antidepressant tablets. He responds only to painful stimuli (Glasgow Coma Score of 8) and he has probably aspirated, because there is right upper lobe consolidation on his chest X-ray. He is hypothermic (34°C) and arterial blood gases on 15 l/min via reservoir bag mask show: pH 7.2, PaCO2 9.5 kPa (73 mmHg), PaO2 12.0 kPa (92.3 mmHg), st bicarbonate 27.3 mmol/l, BE −2. His blood pressure is 80/50 mmHg and his pulse is 120/min. The attending doctor changes his oxygen to a 28% Venturi mask because of his high CO2 and repeat blood gases show: pH 7.2, PaCO2 9.0 kPa (69.2 mmHg), PaO2 6.0 kPa (46.1 mmHg), st bicarbonate 26 mmol/l, BE −2. What would your management be?

7 A 70-year-old woman with severe COPD (FEV1 0.6) is admitted with a chest infection and breathlessness far worse than usual. She is agitated on arrival and refuses to wear an oxygen mask. She is therefore given 2 l/min oxygen via nasal cannulae. Half-an-hour later, when the doctor arrives to re-assess her, she is unresponsive. What do you think has happened?

8 A 50-year-old man is recovering from an exacerbation of COPD in hospital. When you go to review him on the ward, you notice that he is being given 2 l/min of oxygen via a Hudson mask. Is this appropriate?

Self-assessment: discussion

1 The fact that this patient is ‘on inhalers for COPD’ does not mean that she actually has a diagnosis of COPD. How was this diagnosis made – on the basis of some breathlessness on exertion and her smoking history, or by
spirometry (the recommended standard)? Even if the diagnosis of COPD is established, is it mild or severe? Her current problem is not COPD at all, but acute severe cardiogenic pulmonary oedema, a condition which causes ventilatory failure. In a 60-year-old smoker with diabetes, a myocardial infarction is a likely cause. Acute hypoxaemia will aggravate cardiac ischaemia and this needs to be borne in mind. The arterial blood gases show a mixed respiratory and metabolic acidosis with relative hypoxaemia. Rather than removing the oxygen in the vague hope that this will ‘treat’ her high CO₂ (which it will not), this patient requires adequate oxygen therapy and treatment for acute left ventricular failure. If optimal medical therapy fails to improve things (i.v. furosemide and nitrates, nebulised salbutamol, with i.v. diamorphine in some patients), non-invasive continuous positive airway pressure (CPAP) may be tried before tracheal intubation and ventilation.

2 No. His pH is normal. Non-invasive ventilation is used for an exacerbation of COPD when the pH falls below normal due to a high PaCO₂. This patient has a high st bicarbonate, presumably in compensation for his chronically high PaCO₂. He should stay on a Venturi mask while unwell.

3 The main reason why this patient’s oxygen saturations are so low is poor perfusion. The PaO₂ is normal on air – this makes pulmonary embolism unlikely in someone so unwell (cancer and chemotherapy are two independent risk factors for pulmonary embolism). This patient is in shock (circulatory failure) as illustrated by the low blood pressure and severe metabolic acidosis on the arterial blood gases. Shocked patients breathe faster because of tissue hypoxia as well as metabolic acidosis. The history and examination will tell you whether or not this shock is due to bleeding (Are the platelets very low?) or severe sepsis (Is the white cell count very low?). Patients with septic shock do not always have the classical warm peripheries and bounding pulses – they can be peripherally vasoconstricted. Management starts with A (airway with oxygen), B (breathing) and C (circulation) (see Box 1.3). This patient requires fluid and you should call for senior help immediately.

4 Methylene blue in the circulation affects the oxygen saturation measurement. Nevertheless, a concerned junior anaesthetist would check the airway (tube position), breathing (listen to the chest and check the ventilator settings) and circulation (measure blood pressure, pulse and assess perfusion) as well as asking for advice.

5 The arterial blood gases show a metabolic acidosis with hypoxaemia. The PaCO₂ is at the upper limit of normal. It should be low in a metabolic acidosis, indicating a relative respiratory acidosis as well. Treatment priorities in this patient are as follows: securing the airway and administering high-concentration oxygen, assessing and treating breathing, and correcting any circulation problems. There is a discrepancy between the SpO₂ of 98% and the arterial blood gas result which shows a PaO₂ of 7.5 kPa (57.6 mmHg). Tied in with the history and ischaemic-looking ECG, the explanation for this is carbon monoxide (CO) poisoning. CO poisoning produces COHb which is
Oxygen therapy

Interpreted by pulse oximeters as HbO₂ causing an overestimation of oxygen saturation. CO poisoning a common cause of death by poisoning in the UK. Mortality is especially high in those with pre-existing atherosclerosis. CO binds strongly to haemoglobin and causes the oxygen dissociation curve to shift to the left, leading to impaired oxygen transport and utilisation. Loss of CO from the body is a slow process at normal atmospheric pressure and oxygen concentration (21%). It takes 4.5 h for the concentration of CO to fall to half its original value. CO removal is increased by increasing the oxygen concentration or by placing the victim in a hyperbaric chamber. This increases the amount of oxygen in the blood, forcing off CO (see Fig. 2.12). Blood gas analysers use co-oximeters which can differentiate between COHb and HbO₂.

There is debate as to whether treatment with hyperbaric oxygen is superior to ventilation with 100% oxygen on an ICU. Five randomised trials to date disagree. Therefore a pragmatic approach is recommended. The following are features which should lead to consideration of hyperbaric oxygen therapy:

- Any history of unconsciousness
- COHb levels of greater than 40% at any time
- Neurological or psychiatric features at the time of examination
- Pregnancy (because the foetal COHb curve is shifted to the left of the mother's)
- ECG changes.

The risks of transporting critically ill patients to a hyperbaric unit also need to be taken into account. Ventilation with 100% oxygen is an acceptable alternative and this treatment should continue for a minimum of 12 h.

6 This is a 25-year-old man with no previous medical problems. He does not have chronic respiratory failure. He will not ‘retain CO₂’ – he has a problem with ventilation. The arterial blood gases show an acute respiratory acidosis with a lower PaO₂ than expected. He requires tracheal intubation to protect his airway and high-concentration oxygen (15 l/min via reservoir bag mask). He has several reasons to have a problem with ventilation – a reduced conscious level and possible airway obstruction, aspiration pneumonia and the respiratory depressant effects of his overdose. His hypotension should be treated with warmed fluid challenges. The drugs he has

<table>
<thead>
<tr>
<th>Oxygen concentration</th>
<th>Half-life of CO (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room air (21%)</td>
<td>240–300</td>
</tr>
<tr>
<td>15 l/min reservoir bag mask (80%)</td>
<td>80–100</td>
</tr>
<tr>
<td>Intubated and ventilated with 100% oxygen</td>
<td>50–70</td>
</tr>
<tr>
<td>Hyperbaric chamber (100% oxygen at 3 atm)</td>
<td>20–25</td>
</tr>
</tbody>
</table>

*Figure 2.12 Half-life of CO depending on conditions.*
taken (which cause cardiac toxicity) combined with hypoxaemia and hypoperfusion could lead to cardiac arrest. Intravenous sodium bicarbonate is indicated in severe tricyclic poisoning. Flumazenil (a benzodiazepine anti-dote) is not advised when significant amounts of tricyclic antidepressants have also been taken as this will reduce the seizure threshold. It is worth measuring creatinine kinase levels in this case as rhabdomyolysis (from lying on the floor for a long time due to drug overdose) would significantly affect fluid management.

7 This case illustrates the fact that 2 l/min via nasal cannulae is not the same as 28% oxygen via a Venturi mask, despite the theoretical oxygen concentrations displayed on the packaging of nasal cannulae. This lady is unconscious because of a high PaCO₂. This has happened either because her clinical condition deteriorated anyway, or because she has (inadvertently) been given a higher concentration of oxygen, or both. As always, start with A (airway), B (breathing – does she need ventilation?), C (circulation) and D (disability) before blood gas analysis.

8 This is a common scenario. Hudson or MC masks must always be set to a minimum of 5 l/min. Significant rebreathing of CO₂ can occur if the oxygen flow rate is set to less than this, because exhaled air may not be adequately flushed from the mask. The way to give low flow oxygen therapy at 2 l/min is to use nasal cannulae.

References


**Further resources**

- [www.brit-thoracic.org.uk/iqs/bts_guidelines_copd_html](http://www.brit-thoracic.org.uk/iqs/bts_guidelines_copd_html) (COPD guidelines with link to the National Institute for Clinical Excellence guidelines)