CHAPTER 2 Oxygen Therapy

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

- Prescribe oxygen therapy
- Know the different devices used to deliver oxygen
- Be able to describe 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 postoperative 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, 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 PaO_2 of less than 8.0 kPa (60 mmHg) or oxygen saturations less than 93%. The normal range

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for arterial blood oxygen is 11–14 kPa (85–105 mmHg) and this 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 haemoglobin concentration.

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The main causes of hypoxaemia are:

- 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 sepsis (discussed further in Chapter 6).

Symptoms and signs of hypoxaemia include:

- Cyanosis
- Breathlessness
- Headache
- Tachycardia/palpitations
- Restlessness
- Confusion

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- Hypertension then hypotension
- Reduced conscious level

The goal of oxygen therapy is to correct alveolar and tissue hypoxia, aiming for a PaO_2 of at least 8.0 kPa (60 mmHg) or oxygen saturations of at least 93% in people who are not at risk of hypercapnic respiratory failure. Aiming for oxygen saturations of 100% is unnecessary and wasteful.

Oxygen Therapy

The British Thoracic Society (BTS) has published guidelines for oxygen use in adults in healthcare and emergency settings which have been endorsed by 22 specialist societies.² The guidelines recommend aiming to achieve normal or near-normal oxygen saturations for all acutely ill patients apart from those at risk of hypercapnic respiratory failure or those receiving terminal palliative care.

Apart from specific circumstances in which 'too much' oxygen is given deliberately as a treatment (e.g. carbon monoxide poisoning, cluster headache, sickle cell crisis, and pneumothorax), oxygen should only be given to treat hypoxaemia, not breathlessness or acute illness *per se*. The BTS guidelines recommend it should be prescribed to achieve a target saturation of 94–98% for all patients or 88–92% for certain patients who are at risk of hyper-capnic respiratory failure. All patients admitted to hospital should be prescribed a target range at the time of admission. The guidelines also state that staff should be trained in the use of different oxygen delivery devices (see Figure 2.1).

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Mask with a reservoir bag

Venturi mask

Figure 2.1 Different oxygen masks. *Source*: Reproduced with permission from Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.

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Oxygen masks are divided in to two groups, depending on whether they deliver a proportion of, or the entire, ventilatory requirement:

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- Low-flow masks: nasal cannulae, Hudson (or MC) masks, and reservoir bag masks
- High-flow masks: Venturi masks

Any oxygen delivery system can also be humidified.

Nasal Cannulae

Nasal cannulae are commonly used because they are convenient and comfortable. Nasal catheters (a single tube inserted in to a nostril with a sponge) are also sometimes used. The oxygen flow rate does not usually exceed 4 L/min 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 patient's 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 his inspiratory flow rate rises to 60 L/min, he 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 Table 2.1. 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

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Oxygen flow rate (L/min)	Inspired oxygen concentration (%)		
1	24		
2	28		
3	32		
4	36		

 Table 2.1
 Theoretical oxygen concentrations for nasal cannulae.

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obstructive pulmonary disease (COPD)³ when low inspiratory flow rates can occur, and therefore higher oxygen concentrations.

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Hudson or MC Masks

Hudson or MC masks (named after Mary Catterall but also referred to as 'medium concentration') 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 this 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 carbon dioxide 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 dead space, it contains little carbon dioxide. 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 twothirds 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 air-tight seal between mask and patient. Entrained air is always inspired as well.

Nasal cannulae, Hudson masks, and reservoir bag masks all deliver a variable concentration of oxygen. They are all called low-flow masks because the highest gas flow that can be delivered is 15L/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.

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Venturi Masks

Venturi masks, on the other hand, are high-flow masks. The Venturi valve utilises the Bernoulli principle which 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 see a small hole. Oxygen is forced through this constriction and the sudden subsequent increase in area creates a pressure gradient which increases the velocity of the gas and entrains room air (see Figure 2.2). 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



Figure 2.2 A 28% Venturi mask. Bernoulli's equation for incompressible flow states that $\frac{1}{2}pv^2 + P = \text{constant}$ (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 pressure drop due to the increase in area. The velocity or flow of the gas increases according to the above equation and entrains air as a result.

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

Table 2.2 Venturi mask flow rates.

Source: Data from Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.

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 with humidified oxygen circuits. The orifice is adjustable and the oxygen flow rate is set depending on what oxygen concentration is desired.

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. Table 2.2 shows the flow rates for various Venturi masks and Figure 2.3 shows the effect of lower total flow rates in patients with high inspiratory demands.

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 postoperative respiratory failure where the expectoration of secretions is important.

Flow Versus Concentration

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

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Figure 2.3 Lower total flow rates in patients with high inspiratory demands. 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%. *Source*: Data provided by Intersurgical Complete Respiratory Systems, Wokingham, Berkshire.

'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 choose not to stock Hudson masks to avoid the potential confusion caused by too many oxygen delivery systems. Table 2.3 shows which mask is appropriate in different clinical situations and Figure 2.4 shows a simple guide to oxygen therapy for acutely ill patients. Oxygen therapy should be goal directed. The right patient should receive the right amount of oxygen for the right length of time.

Can Oxygen Therapy Be Harmful?

It has been a longstanding cultural norm to give oxygen to any sick patient regardless of their oxygen saturations⁴ and this is still sometimes taught in courses. But there is increasing evidence that too much oxygen can be harmful in some situations.

*Hyper*oxaemia can sometimes have adverse effects. It increases systemic vascular resistance which may be a disadvantage in some patients (e.g. myocardial infarction and stroke). A clinical practice guideline published in 2018, based on a systematic review of the literature,

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Oxygen mask	Clinical situation
Nasal cannulae (2–4 L/min)	Patients with otherwise normal physiology (vital signs) e.g. slightly low SpO ₂ , long-term oxygen therapy
Hudson masks (more than 5 L/min) or reservoir bag masks (more than 10 L/min)	Higher concentrations required and controlled oxygen not necessary e.g. severe asthma, acute left ventricular failure, and
Venturi masks	Controlled oxygen therapy required e.g. patients at risk of hypercapnic respiratory failure (COPD obesity hypoventilation syndrome, chronic musculoskeletal, or neurological disorders)

Table 2.3 Which mask for which patient?

Oxygen therapy is indicated in:

- Hypoxaemia
- Other conditions as directed by doctor



Figure 2.4 Simple guide to oxygen therapy for acutely ill patients. Nasal cannulae should ideally *not* be used in severe acute exacerbations of COPD because they deliver a variable concentration of oxygen.

stated with moderate certainty that oxygen increases mortality when the SpO_2 is above 96% and recommended target saturations of no higher than 96% for all patients.⁴ For patients with myocardial infarction and stroke, it recommended against initiating oxygen therapy if the initial SpO_2 is above 92%.

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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 in to the bloodstream, leaving the alveoli to collapse. Acute lung injury is thought to be due to oxygen free radicals. Oxygen is also combustible. Being attached to oxygen hampers mobility. 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.

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But!

Hypoxaemia can kill. 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)
- Ventilation-perfusion (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. sepsis, malignant hyperthermia, and sodium bicarbonate infusion) where the patient cannot compensate by an overall increase in alveolar ventilation
- Increased inspired PaCO₂ (e.g. breathing in to a paper bag)

Figure 2.5 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



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increased respiratory rate. Respiratory muscle strength can be reduced by a problem in any part of the neuro-respiratory pathway – motor neurone disease, Guillain–Barré syndrome, myasthenia gravis, critical illness polyneuropathy/myopathy, 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 an opioid overdose.

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A problem with ventilation is one of the most common causes of hypercapnia among patients admitted to hospital. Examples include the overdose patient with airway obstruction, the 'tired' asthmatic, the obese patient with pneumonia, the patient recovering from a laparotomy on an opiate 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 all of the examples listed above, oxygen therapy is not a cause of hypercapnia.

There are many conditions in which chronic hypercapnia occurs – severe chest wall deformity, morbid obesity, and neurological conditions causing muscle weakness are examples. The reasons for chronic hypercapnia in chronic obstructive pulmonary disease (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 FEV_1 is less than 1 L.

For the purposes of explanation here, the term $^{\circ}CO_2$ 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.

CO₂ Retention

In 1949, a case was described of a man with emphysema who lapsed in to a coma after receiving oxygen therapy but rapidly recovered after the oxygen was removed.⁵ 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.⁶ In a further study, it was showed that stopping and starting oxygen therapy led to a fall and rise in $PaCO_2$, respectively.⁷ These early experiments led to the concept of 'hypoxic drive' attributed to Campbell,⁸ which is often 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 only occurs at altitude or during illness. If these patients are given too much oxygen, their 'hypoxic drive' is abolished, ventilation is reduced, and $PaCO_2$ will rise as a result, causing CO_2 narcosis and eventually apnoea.

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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 debunked this theory and it is now thought that changes in ventilation-perfusion (V/Q) are more important in the actiology of CO_2 retention.⁹ 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 ventilation-perfusion. PaCO₂ rises because more CO₂-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 ventilation-perfusion plus the inability to compensate is why CO₂ 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.^{10,11} Oxygen also causes the CO₂ dissociation curve in red blood cells to shift to the right (the Haldane effect) and in people with severe COPD who cannot compensate by increasing their alveolar ventilation, this also contributes to CO₂ retention.12

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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 patients with COPD are fairly physiologically normal. This may explain some 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.¹³

Half of admissions with an acute exacerbation of COPD have reversible hypercapnia.^{14,15} In other words, these people have acute but not chronic respiratory failure. Non-invasive ventilation has been shown to be a successful treatment for acute respiratory failure, or acute on chronic respiratory failure, leading to a reduction in mortality and length of hospital stay.¹⁶ 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 blood gases, medical therapy, and ventilation if needed?

Table 2.4 is a simplified guide to the clinical differences between CO_2 retainers and patients with ventilatory failure and COPD. Of course, many patients will fall in between these two extremes but it is nevertheless a useful guide, especially when teaching.

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Likely CO ₂ retention	Likely ventilatory failure
Usually severely limited by breathlessness	Not usually limited by breathlessness
Cor pulmonale or polycythaemia present	No signs of chronic hypoxaemia
FEV ₁ less than 1 L	FEV ₁ good
On home nebulisers and/or home oxygen	Inhalers only
Abnormal blood gases when well	Normal blood gases when well
Admission blood gases show pH and st bicarbonate/BE consistent with chronic respiratory failure	Admission blood gases show pH and st bicarbonate/BE not consistent with chronic respiratory failure
Not critically ill	Critically ill
Reasonable air entry	Silent chest or feeble chest movements
	Dubious diagnosis of COPD
	Chest X-ray shows pulmonary oedema or severe pneumonia

Table 2.4 CO₂ retention due to oxygen therapy versus ventilatory failure in patients with COPD.

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One in five patients with COPD admitted to hospital has a respiratory acidosis. The more severe the acidosis, the greater the mortality. Some of this acidosis may be caused by uncontrolled oxygen therapy, since a proportion disappears quickly after arrival in hospital,¹⁷ although this may also be due to treatment with bronchodilators. Guidelines recommend using Venturi masks in conjunction with pulse oximetry for exacerbations of COPD until further information can be gained from arterial blood gases.¹⁸ 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 COPD¹⁹ in which 101 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 hour. 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 intensive care specialists and it is worth reading in full.²⁰ 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,²¹ outcome studies which ignore it are meaningless. They finished by saying, 'We frequently attend emergency 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.'

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 treatment.

To summarise:

- One of the most common causes of hypercapnia among patients admitted to hospital 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 blood gases (see Figure 2.4)
- Controlled oxygen therapy, medical treatment, and ventilation is used to treat acute respiratory acidosis (low pH due to a high PaCO₂) in exacerbations of COPD

Pulse Oximetry

Pulse 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. The Lambert and Beer Laws describe this. Oxyhaemoglobin (HbO₂) and deoxyhaemoglobin (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. Because 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 (Figure 2.6).

Oximeters are calibrated by the manufacturers using data that was originally obtained by human volunteers. SpO_2 was measured while the volunteers inspired various oxygen concentrations. Because of 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 (PaO_2) through the oxygen dissociation curve. Remembering this indirect relationship is important, because SpO_2 is

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Figure 2.6 Absorption in a pulse oximeter. Components of absorption. Tissue, venous blood (V), arterial blood (A), and pulsatile arterial blood.

affected by several internal factors (see Figure 2.7) as well as external factors, listed below. It is also important to remember that SpO_2 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 and gel nails interfere with the signal
- Anaemia at a Hb of 8g/dL, the oxygen saturation is underestimated by 10–15%, especially at lower saturation levels

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Figure 2.7 The oxygen dissociation curve. 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-DPG, and acidosis (the shift caused by pH is called the Bohr effect). This means P_{50} 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 P_{50} reduces and lower pulmonary capillary saturations are required to saturate Hb, but lower tissue capillary PaO₂ is required before oxygen is delivered.

- 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:

Hb in g/dL×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:

Hb (×10 to convert to litres)×SaO₂×1.3×CO in L/min

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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 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 intensive care unit, 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 $14 \times 0.95 \times 1.3 \times 10 \times 5 = 864.5 \text{ mLO}_2/\text{min}$. 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 $14 \times 0.93 \times 1.3 \times 10 \times 4$ = 677 mLO₂/min. By increasing his oxygen so that his saturations are now 98%, his oxygen delivery can be increased to 713 mLO₂/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 mLO₂/min. Oxygen delivery has been increased *more* by giving fluid than by giving oxygen.

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The oxygen delivery equation also illustrates the relationship between SaO_2 and haemoglobin. An SaO_2 of 95% with severe anaemia is worse in terms of oxygen delivery than an SaO_2 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% in most patients
- Special considerations are required in patients with COPD or other causes of chronic respiratory failure, and *hyper*oxaemia should be avoided in acute myocardial infarction and stroke
- Oxygen masks are divided in to two groups: low-flow masks which deliver a variable concentration of oxygen (nasal cannulae, Hudson masks, and reservoir bag masks) and high-flow Venturi masks which deliver a fixed concentration of oxygen
- The most common cause of hypercapnia for patients admitted to hospital is ventilatory failure. This has nothing to do with oxygen therapy – treat the cause
- Pulse oximetry is a measure of oxygenation, not ventilation
- Oxygen is delivered to the tissues via the airways, breathing, and circulation

Self-Assessment: Case Histories

1 A 60-year-old woman arrives in the emergency department with acute breathlessness. She was given 12 L/min oxygen via Hudson 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 pulmonary oedema. Her blood gases are: pH 7.15, PaCO₂ 8.0 kPa (61.5 mmHg), PaO₂

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9.0 kPa (69.2 mmHg), st bicarbonate 20 mmol/L, and 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 82%. Her blood pressure is 180/70 mmHg. Comment on her oxygen therapy. What is your management?

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- 2 A 50-year-old man is admitted 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), standard bicarbonate 35 mmol/L, st bicarbonate 38.4 mmol/L, and 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 chemotherapy in-patient 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 130/min, blood pressure 70/40 mmHg, respiratory rate 40/min, and the patient is 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, and 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 is brought unconscious to 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, and oxygen saturations 98% on 15L/min oxygen via reservoir bag mask. His ECG shows wide-spread 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, and BE –10. His full blood count is normal. What is the explanation for the discrepancy in the SpO₂ and PaO₂? What is your management?
 - A 25-year-old man with no past medical history is found on the floor at home having taken a mixed overdose of benzodiazepines and tricyclic antidepressants. 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, and 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, and BE -2. What is your management?

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Self-Assessment: Discussion **31**

- 7 A 70-year-old woman with severe COPD (FEV₁ 0.6 L) is admitted with a chest infection and breathlessness which is 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 reassess 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 2L/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 pulmonary oedema, a condition which can cause ventilatory failure. In a 60-year-old smoker with diabetes, a myocardial infarction is a likely cause. Acute hypoxaemia will aggravate cardiac ischaemia which will only make things worse. The arterial blood gases show a mixed respiratory and metabolic acidosis and her current oxygen saturations are 82% on air. Rather than removing the oxygen in the vague hope that this will 'treat' her high CO_2 (which it will not), this patient requires oxygen therapy and treatment for acute pulmonary oedema. If optimal medical therapy fails to improve things (e.g. intravenous furosemide and nitrates, nebulised salbutamol), non-invasive ventilation may be initiated as treatment for pulmonary oedema (see Chapter 4).
- 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 in compensation for his chronically high PaCO₂. He should stay on a Venturi mask while unwell.
- 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 as illustrated by hypotension and a 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 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 sometimes be peripherally shut down. 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.

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Table 2.5	Half-life	of CO	depending	on	conditions
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Conditions	Half-life of CO (minutes)
Room air (21% oxygen)	240-300
15 L/min reservoir bag mask (up to 80% oxygen)	80-100
Intubated and ventilated with 100% oxygen	50-70
Hyperbaric chamber (100% oxygen at 3 atmospheres)	20-25

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4 Methylene blue in the circulation affects pulse oximetry measurements. There is a reduced SpO_2 but a normal SaO_2 and PaO_2 . The dye is used in urological and gynaecological surgery to locate portions of the urinary tract or fallopian tubes. It disturbs light absorbance in the 600–700 nm range in a concentration-dependent manner. SpO_2 readings return to normal within minutes due to rapid redistribution of the dye and its metabolism in the kidneys. Nevertheless, a concerned 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) in order to double check that all was well.

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 respiratory acidosis is present as well. Treatment priorities in this patient are as follows: securing the airway and administering oxygen, assessing and treating breathing, and correcting any circulation problems. There is a discrepancy between the SpO_2 of 98% and the arterial blood gas result which shows a PaO_2 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 carboxyhaemoglobin which is interpreted by pulse oximeters as oxyhaemoglobin causing an overestimation of oxygen saturation. In CO poisoning, mortality is especially high in people with pre-existing ischaemic heart disease. 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 hours for the concentration of CO to fall to half its original value. CO removal is increased by increasing the oxygen concentration (e.g. ventilation with 100% oxygen for at least 12 hours) or by placing the patient in a hyperbaric chamber. This increases the amount of oxygen in the blood, forcing off CO (see Table 2.5). Blood gas analysers use co-oximeters which can differentiate between carboxyhaemoglobin and oxyhaemoglobin.

The following are features which should lead to consideration of hyperbaric oxygen therapy:

- Any history of unconsciousness
- Carboxyhaemoglobin (COHb) levels of greater than 40% at any time
- Neurological or psychiatric features at the time of examination

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- 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 in to account. Ventilation with 100% oxygen is an acceptable alternative and this treatment should continue for a minimum of 12 hours.

- 6 This is a 25-year-old man with no previous medical history. He does not have chronic respiratory failure. He will not 'retain CO_2 ' he has a problem with ventilation. The arterial blood gases show an acute respiratory acidosis with a lower PaO_2 than expected. He requires tracheal intubation to protect his airway, and oxygen. 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 taken cause cardiac toxicity, and combined with hypoxaemia, hypotension, and hypothermia, could lead to cardiac arrest. Intravenous sodium bicarbonate is indicated in severe tricyclic poisoning. Flumazenil (a benzodiazepine antidote) should not be given when significant amounts of tricyclic antidepressants have also been taken as this can cause seizures. It is worth measuring creatinine kinase levels in this case as rhabdomyolysis (from lying on the floor for a long time and also due to the drugs taken) may significantly alter fluid management.
- 7 This case illustrates the fact that 2L/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 patient is probably unconscious because of a high PaCO₂. This has happened either because her clinical condition deteriorated, or because she has inadvertently been given a higher concentration of oxygen due to the use of nasal cannulae or both. As always, quickly start with A (airway), B (breathing does she need immediate ventilation?), C (circulation), and D (disability) and then blood gas analysis.
- 8 Hudson masks must be set to a minimum of 5 L/min. Significant rebreathing of carbon dioxide 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

- 1 Cooper NA. Oxygen therapy myths and misconceptions. *Care Crit Ill* 2002; 18(3): 74–77.
- **2** O'Driscoll BR, Howard LS, Earis J, Mak V, on behalf of the British Thoracic Society Emergency Oxygen Guideline group. BTS guidelines for oxygen use in adults in healthcare and emergency settings. *Thorax* 2017; 72: i1–i90.
- **3** Davies RJO, Hopkin, JM. Nasal oxygen in exacerbations of ventilatory failure: an underappreciated risk. *BMJ* 1989; 299: 43–44.
- 4 Siemieniuk RAC, Chu DK, Ha-Yeon Kim L et al. Oxygen therapy for acutely ill medical patients: a clinical practice guideline. *BMJ* 2018; 363: k4169.

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 (\bullet)

- 5 Donald KW. Neurological effect of oxygen. Lancet 1949; ii: 1056–1057.
- **6** Prime FJ, Westlake EK. The respiratory response to CO2 in emphysema. *Clin Sci* 1954; 13: 321–332.
- **7** Westlake EK, Simpson T, Kaye M. Carbon dioxide narcosis in emphysema. *Q J Med* 1955; 94: 155–173.
- 8 Campbell EJM. The management of respiratory failure in chronic bronchitis and emphysema. *Am Rev Respir Dis* 1967; 96: 626–639.
- **9** Abdo WF, Heunks LMA. Oxygen-induced hypercapnia in COPD: myths and facts. *Crit Care* 2012; 16: 323.
- **10** Aubier M, Murciano D, Milic-Emili J et al. Effects of administration of oxygen on ventilation and blood gases in patients with chronic obstructive pulmonary disease. *Am Rev Respir Dis* 1980; 122: 191–199.
- **11** Hanson CW III, Marshal BE, Frasch HF et al. Causes of hypercarbia with oxygen therapy in patients with chronic obstructive pulmonary disease. *Crit Care Med* 1996; 24: 23–28.
- **12** Aubier M, Murciano D, Milic-Emili J et al. Effects of the administration of O2 on ventilation and blood gases in patients with chronic obstructive pulmonary disease during acute respiratory failure. *Am Rev Respir Dis* 1980; 122: 747–754.
- 13 Gomersal CD, Joynt GM, Freebairn RC, Lai CKW, Oh TE. Oxygen therapy for hypercapnic patients with chronic obstructive pulmonary disease and acute respiratory failure: a randomised controlled pilot study. *Crit Care Med* 2002; 30(1): 113–116.
- **14** Costello R, Deegan P, Fitzpatrick M et al. Reversible hypercapnia in chronic obstructive pulmonary disease: a distinct pattern of respiratory failure with a favourable prognosis. *Am J Med* 1997; 102: 239–244.
- **15** McNally E, Fitzpatrick M, Bourke S. Reversible hypercapnia in acute exacerbations of chronic obstructive pulmonary disease (COPD). *Eur Respir J* 1993; 6: 1353–1356.
- **16** Plant PK, Owen JL, Elliot MW, The YONIV trial. A multi-centre randomised controlled trial of the use of early non-invasive ventilation for exacerbations of chronic obstructive pulmonary disease on general respiratory wards. *Lancet* 2000; 355: 1931–1935.
- 17 Plant PK, Owen JL, Elliot MW. One year period prevalence study of respiratory acidosis in acute exacerbations of COPD: implications for the provision of non-invasive ventilation and oxygen administration. *Thorax* 2000; 55: 550–554.
- 18 British Thoracic Society. Guidelines for the management of acute exacerbations of COPD. *Thorax* 1997; 52(suppl 5): S16–S21.
- **19** Denniston AKO, O'Brien C, Stableforth D. The use of oxygen in acute exacerbations of chronic obstructive pulmonary disease: a prospective audit of pre-hospital and emergency management. *Clin Med* 2002; 2(5): 449–451.
- 20 Singer M, Bellingan G. Letter to the editor. Clin Med 2003; 3(2): 184.
- 21 Smith I, Kumar P, Molloy S, Rhodes A et al. Base excess and lactate as prognostic indicators for patients admitted to intensive care. *Intensive Care Med* 2001; 27: 74–83.

Further Resources

Moyle J. Pulse Oximetry, 2nd edition (principles and practice series). London, BMJ Books, 2002. ISBN 0 7279 1740 4.

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