The clinical use of oxygen in hospitals with limited resources

Guidelines for health-care workers, hospital engineers and managers

The World Health Organization
Editor: Trevor Duke
November 2011
We are grateful to the following people who contributed to the writing of chapters of these guidelines: David Peel, Harry Campbell and Iain Wilson (UK); Suzanne Carai (WHO Geneva); Martin Weber (WHO Indonesia); Berhard Frey (Switzerland); Penny Enarson (France); Mike English (Kenya); Bob Jacobson, Kathy Sanchez and Ravi Bansal (USA).

We thank the following people who reviewed the guidelines or contributed to ideas contained within them: Sens Matai, Francis Wandi and Merilyn Jonathan (PNG); Sophie La Vincente, Rami Subhi, Dave Tickell, Eleanor Neal and Amy Auge (Australia); Steve Howie (the Gambia); Grace Irimu (Kenya); Sandro Contini (Italy); Mike Dobson and Brigid Hayden (UK); KA Kelly McQueen and Hilary Cohen (USA).

We are grateful to the following WHO staff for coordination and review of the guidelines: Martin Weber, Susanne Carai, Meena Cherian, Kathrin Müller-Wielsch, Wilson Were, Shamin Qazi, Olivier Fontaine and Samira Aboubaker.

We also thank David Woodroffe, David Woodroffe Digital Illustration, for preparing the illustrations included throughout the guidelines.
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Acronyms and abbreviations

AC alternating current
ALRI acute lower respiratory infection
CE marking CE marking is a declaration by the manufacturer that the product meets all the appropriate provisions of the relevant legislation implementing certain European Directives. CE is not an acronym for specific words. The CE marking (also known as CE mark) is a mandatory conformity mark on many products placed on the single market in the European Economic Area (EEA). The CE marking certifies that a product has met EU consumer safety, health or environmental requirements
CO Carbon monoxide
COPD chronic obstructive pulmonary disease
CPAP continuous positive airway pressure
DC direct current
F French (measure of catheter diameter)
FiO2 fraction of inspired oxygen
H2O water
IEC International Electrotechnical Commission
ISO International Organization for Standardization
N-P nasopharyngeal
PaO2 partial pressure of oxygen
PCB printed circuit board
PEEP positive end expiratory pressure
POC portable oxygen concentrator
PSA pressure swing adsorption
SaO2 arterial haemoglobin oxygen saturation
SD standard deviation
Sp pulse saturation
SpO2 haemoglobin oxygen pulsed saturation as measured by pulse oximetry
WHO World Health Organization

Units

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<tr>
<th>cm</th>
<th>centimetre</th>
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<tr>
<td>dBA</td>
<td>decibels adjusted</td>
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<td>Hz</td>
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<td>kg</td>
<td>kilograms</td>
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<tr>
<td>kPa</td>
<td>kilopascals</td>
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<tr>
<td>mm Hg</td>
<td>millimetres of mercury</td>
</tr>
<tr>
<td>psi</td>
<td>pounds per square inch</td>
</tr>
<tr>
<td>V</td>
<td>volts</td>
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<tr>
<td>V/Q</td>
<td>ventilation to perfusion ratio</td>
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<td>W</td>
<td>watts</td>
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<td>°C</td>
<td>degrees celsius</td>
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Introduction

Every year nearly 9 million children die, mostly from preventable or easily treatable diseases, and more than 95% of these deaths occur in developing countries. Pneumonia is the leading cause of death in children under-5 years of age, being responsible for at least 19% of all deaths in this age category.\(^1\) Hypoxaemia (insufficient oxygen in the blood) is the major fatal complication of pneumonia, and increases the risk of death many times. It is estimated that at least 13.3% of children with pneumonia have hypoxaemia.\(^2\) Each year 11–20 million children are admitted to hospitals with pneumonia.\(^3\) This corresponds to 1.5–2.7 million cases of hypoxaemic pneumonia each year.

A further 40% of the 9 million annual child deaths result from neonatal conditions such as birth asphyxia, sepsis and low birth weight, all of which can lead to hypoxaemia. This adds to the substantial burden of hypoxaemia, especially in developing countries.

In adults, many conditions are commonly associated with hypoxaemia, particularly chronic obstructive pulmonary disease, asthma, pneumonia, heart failure, major trauma and obstetric emergencies.

Despite its importance in virtually all areas of acute severe illness, hypoxaemia is often not well recognised or managed in settings where resources are limited. Oxygen treatment remains an inaccessible luxury for a large proportion of severely ill patients admitted to hospitals in developing countries. This is particularly true for patients in small district hospitals, where, even if some facility for delivering oxygen is available, supplies are often unreliable and the benefits of treatment may be diminished by poorly maintained, inappropriate equipment, poorly trained staff or inadequate guidelines.

Increasing awareness of these problems is likely to bring considerable clinical and public health benefits. Health workers should know the clinical signs that suggest the presence of hypoxaemia; however, more reliable detection of hypoxaemia could be achieved through more widespread use of pulse oximetry (which gives a non-invasive measure of arterial oxygen saturation). Oxygen therapy needs to be more widely available, and in many remote settings this could be achieved with greater use of oxygen concentrators.

Experience is growing in the clinical, organizational, biomedical technology and training aspects of setting up and sustaining effective oxygen delivery systems in hospitals and small health facilities in many developing countries. There is strong evidence that the use of pulse oximetry and availability of reliable oxygen sources in district and provincial hospitals can reduce death rates from pneumonia by about one third.\(^4\)

Much of the evidence and experience drawn on here comes from the care of sick children, because young children are affected disproportionately by hypoxaemia and most research on hypoxaemia has been in paediatrics. The principles, however, are equally relevant to setting up and managing services for adults; the use of oxygen in trauma and surgery is relevant to all age groups, and there is now increasing experience in managing hypoxaemic illnesses in adults.

Even in settings where systems and management are imperfect, substantial improvements can be made. While these guidelines contain a prescription for establishing quality oxygen delivery, doctors, nurses and managers should not be discouraged if they feel they
cannot get everything right immediately. In many countries, despite imperfect and fragile health services, lives are being saved and the quality of treatment is improving.

Before we start, some words on the structure of this manual.

Part I contains general information that is useful to all those interested in the delivery of oxygen in hospitals with limited resources. It provides basic information about hypoxaemia and its detection, and about oxygen delivery systems. In addition, this part contains some case studies that demonstrate how oxygen can be delivered in resource-poor settings.

Part II contains three sections: for clinicians, engineers and programme managers. Each section contains detailed information relevant to the particular profession. These roles, however, often overlap in small hospitals. For example, clinicians often have administrative responsibilities and some aspects of equipment maintenance will be done by nurses rather than engineers. The choice of the most appropriate oxygen source and delivery method will require clinicians, engineers and administrators working together. Engineers need to know something about pulse oximeter attachments, but these are described in the section for clinicians, as they are the main users. Clinicians need to know something about the workings of oxygen concentrators, but this is described in detail in the section for engineers, as they are most involved in maintenance of the concentrators. Administrators are responsible for seeing that all professional groups are well trained and that the resources are available for them to do their jobs.

Finally, Part III contains annexes that include useful tools such as guidelines and procurement questionnaires.

We hope that these guidelines will stimulate efforts to improve oxygen supply systems worldwide, and will provide useful guidance to health staff to make these improvements.
Part I  Basic information for all professional groups

KEY MESSAGES

- Hypoxaemia means low oxygen levels in the blood. It is a life-threatening condition that occurs frequently in pneumonia, common neonatal conditions, chronic obstructive pulmonary disease, trauma, and obstetric and perioperative emergencies.
- The best way to detect and monitor hypoxaemia is with pulse oximetry. Oximetry is accurate, simple, non-invasive and cost-efficient. Where pulse oximetry is not available, it is important to examine for clinical signs of hypoxaemia.
- Hypoxaemia can be treated easily by giving oxygen to the patient.
- For hospitals with limited resources, oxygen concentrators are the most reliable, cost-efficient source of oxygen, as long as there is a continuous power supply.
- There are several devices for giving oxygen to a patient. Nasal prongs or nasal/nasopharyngeal catheters allow the most efficient delivery of oxygen.
- A successful oxygen system requires clinicians, engineers and administrators working together. Careful planning is necessary, as well as cooperation and communication between all groups.
- Do not be discouraged by difficulties or obstacles – progress always takes time, and even small improvements can save the lives of many patients with hypoxaemia.
1 Introduction to hypoxaemia

This chapter contains basic information on hypoxaemia and how it can be detected. More detailed information on hypoxaemia can be found in Part II, section A (Information for clinicians).

1.1 What is hypoxaemia?

Hypoxaemia means low levels of oxygen in the blood. It occurs frequently in diseases like pneumonia or chronic obstructive pulmonary disease (COPD). As all functions within the human body require oxygen, a lack of oxygen will lead to dysfunction of the organ systems very quickly. Therefore, hypoxaemia is a life-threatening condition that requires early detection and treatment.

The main carrier of oxygen in the blood is haemoglobin. To measure blood oxygen levels, we commonly use arterial haemoglobin oxygen saturation (SaO2). When measured by pulse oximetry, the abbreviation is SpO2 (haemoglobin oxygen pulsed saturation). The normal range of SpO2 at sea level is 96–100%.5 An SpO2 <90% is considered by most clinicians as an appropriate indication for giving oxygen.

In a systematic review of more than 20 000 children with acute pneumonia or other lower respiratory tract infection, the median hypoxaemia prevalence of children with pneumonia requiring hospitalization (severe and very severe pneumonia using the WHO clinical classification), was 13.3% (9.3–37.5%).2 Given that 11–20 million children each year are admitted to hospitals with pneumonia,3 this corresponds to 1.5–2.7 million cases of hypoxaemic pneumonia presenting to health facilities each year, and countless more do not make it to health facilities.

To learn more about hypoxaemia, see Chapter 4.

1.2 How can hypoxaemia be detected?

Severe hypoxaemia can often be recognized by certain clinical signs; fast breathing, severe chest indrawing, blue colouring of tongue or gums (central cyanosis), nasal flaring or grunting with every breath. These are important signs for all health workers to know, and it is essential for health workers to be able to recognize the generally very sick patient. However, even the best observations of clinical signs commonly misdiagnose hypoxaemia in children with normal oxygen saturation, or fail to detect hypoxaemia in others.

Pulse oximetry is the most accurate non-invasive method of detecting hypoxaemia. It measures the percentage of oxygenated haemoglobin in arterial blood (SpO2). The pulse oximeter consists of a computerized unit and a sensor probe, which is attached to the patient’s finger, toe or earlobe. The oximeter displays the SpO2, together with an audible signal for each pulse beat, a pulse rate and, in most models, a graphical display of the blood flow past the probe (the plethysmographic or pulse wave). The technology is robust and the costs are quite low. Oximeters may be used to detect and monitor hypoxaemia. Oximeters can make the use of oxygen supplies more efficient and improve patient monitoring, and they are cost effective for district hospitals.6
Blood gas analysis is also a very accurate method of detecting hypoxaemia. It measures the partial pressure of oxygen (PaO$_2$) and carbon dioxide in blood, and gives additional information on blood pH and concentrations of the main electrolytes. However, blood gas analysis has several drawbacks. Blood gas analysers are very expensive, and the chemical reagents are a high ongoing cost, which may be unaffordable in hospitals with limited resources. Inaccurate measurements can easily result from factors such as a poorly taken sample (especially from a struggling or uncooperative child), delay in transfer to a laboratory, inadequate storage conditions before analysis, and inadequate maintenance or quality control within the laboratory. The method is also invasive and uncomfortable, as it requires the taking of blood. Therefore, blood gas analysis is not suitable for most hospitals with limited resources.

To learn more about the detection of hypoxaemia and the function of pulse oximeters and blood gas analysers, see Chapters 5 and 11, and Annex A. Chapters 12 and 13 give more information on the advantages and disadvantages of the methods described.
This chapter contains general information on how to give oxygen in hospitals with limited resources. It briefly describes oxygen sources and delivery methods. For more information on administering oxygen, please refer to the relevant sections in Part II, sections A and B (Information for clinicians and engineers).

2.1 Sources of oxygen

The most common sources of oxygen are oxygen cylinders, oxygen concentrators and oxygen pipelines.

Oxygen for cylinders is produced by cooling air until it liquefies, then distilling the liquid to separate pure oxygen from it. This is an expensive, energy-consuming process that can only take place in large manufacturing plants. Cylinders need to be transported to and from the bulk supply depot for refilling. Transport is difficult, expensive and often unreliable in developing countries, so small hospitals can be without oxygen supplies for long periods.

Oxygen concentrators entrain air from the environment, which usually contains 21% oxygen, 78% nitrogen and 1% other gases. By extracting nitrogen from the air, they can produce almost pure oxygen. Most concentrators supply oxygen at a concentration of 90–96%. In paediatric care, with a continuous and reliable power source, one oxygen concentrator can supply continuous oxygen for up to four patients. (In case of power failure, a power generator or a power-independent oxygen source should be available as a back-up.) Concentrators need regular maintenance to ensure proper function, but they are a reliable and independent oxygen source that is also cost-efficient. To get the most out of concentrators they should be used with flow splitters or flow meters that allow oxygen to be provided to multiple patients at the same time.

In many larger hospitals, oxygen is distributed through a system of copper pipes from a central source of oxygen, usually located outside the building. The source may be liquid oxygen, high-pressure gaseous oxygen cylinders, a large oxygen concentrator or a combination of these. Pipeline systems supply oxygen at high pressure, which enables equipment such as anaesthetic machines and ventilators to be supplied with the gas. A pipeline system has many safety advantages: it reduces the risk of fire and avoids handling and transportation between hospital wards of heavy cylinders. However, the high cost of installing centralized oxygen sources with copper pipelines, and their maintenance, make these systems of oxygen delivery unsuitable for many district-level hospitals in developing countries.

To learn more about the different sources of oxygen, see Chapters 7 and 12. For use and daily maintenance, see Chapters 6, 7, 9 and 12. See Annexes A and B for details on function, installation and advanced maintenance. See Chapter 12 for recommendations on procurement.
2.2 Devices for giving oxygen

The devices used to give oxygen to a patient should be safe, simple, effective and inexpensive. Some methods for giving oxygen are non-invasive (delivery through a face mask, into a head box, incubator or tent, or through tubing held close to an infant’s face) and others are semi-invasive (insertion of nasal prongs or catheters into the upper airway).7 The pros and cons of different methods have been reviewed.7,8

Non-invasive methods require high oxygen flow and are therefore inefficient and uneconomical where resources are limited. Semi-invasive methods use lower flows and are therefore more appropriate where oxygen supplies are scarce. Some semi-invasive devices have an additional beneficial effect on lung function by producing positive end expiratory pressure (PEEP).9 This kind of PEEP production can also be effective in the management of apnoea (associated with prematurity or with bronchiolitis).10

Problems associated with oxygen delivery systems include dislodgement of nasal prongs and obstruction of catheters. Hypercapnoea (high levels of carbon dioxide in the blood) can result from inadequate flows through head boxes or facemasks that allow build-up of carbon dioxide. Nasopharyngeal (N-P) catheters, and to a lesser extent nasal catheters, can obstruct airways or cause bleeding.11 Uncontrolled high PEEP production associated with inappropriately high oxygen flows through nasal catheters may lead to gastric distension or pneumothorax.

To learn more about devices for giving oxygen to different patient groups, see Chapters 6 and 9.
3 Oxygen systems in hospitals

This chapter contains general information on oxygen systems used in hospitals and on the importance of working together. For more details on what to consider when setting up an oxygen system, see Part II, section C (Information for hospital administrators and managers).

3.1 Availability of oxygen in small hospitals

Many hospitals in developing countries do not have access to reliable supplies of oxygen, making hypoxaemia a serious unaddressed problem. While most hospitals have some oxygen supplies, there are frequently difficulties with its use. For example, some of the equipment necessary for delivering oxygen may not be available or supplies of cylinder oxygen might be depleted. There may be no protocols for when and how to give oxygen, how to monitor oxygen use and when to stop it. Oxygen concentrators may be available, but have no power to run them.

There are several published reports on the availability and use of oxygen in small hospitals and primary health facilities in developing countries. In one study of district hospitals in seven developing countries, three quarters had oxygen available somewhere within the hospital, but only half had oxygen available in the outpatient or emergency areas. In another survey of 14 district hospitals in Kenya, 10 reported that they always had access to some oxygen. However, some of these 10 hospitals sometimes had no access to flow meters, oxygen tubing or suction. Only 60% of children prescribed oxygen by a doctor in an emergency department actually received it. Often, health workers are faced with deciding which child, of several needing it, should receive the available oxygen. No hospital in this Kenyan survey had guidelines for how to prioritize children in such a situation.

Often, demand and supply are unevenly matched. In five hospitals in Papua New Guinea, oxygen was not available on the day of admission for 22% of 1300 children, including 13% of children who were assessed as hypoxaemic at admission.

Generally, oxygen is much less likely to be available in primary health clinics or smaller remote hospitals. A survey of primary health clinics in South Africa found that only 61% had oxygen, and the availability of oxygen varied widely in regions throughout that country. The findings of a survey of 13 district hospitals in 7 developing countries suggest that secondary referral hospitals generally have better oxygen systems than district hospitals. In Papua New Guinea, oxygen was less available in remote, rural, district hospitals than in provincial hospitals in major towns.

Where oxygen concentrators are used availability of a reliable power supply is crucial. In Sierra Leone, 40% of hospitals had no oxygen supply, while the remaining 60% had interrupted supplies because of shortages of mains power, and a scarcity of fuel to run generators. In the Gambia, a survey found that out of 11 facilities that managed severe pneumonia, oxygen was available in only 6, and only 3 of these had a reliable supply.
3.2 What is important for setting up and maintaining an oxygen system?

A number of issues need to be considered to ensure oxygen systems are both effective and safe for all involved. The most basic items needed to successfully implement an oxygen supply system are outlined below.

- A multidisciplinary oxygen team, including a biomedical engineer, a senior clinician (such as a paediatrician, physician or child-health nurse) and an administrator, is desirable to support the clinical, programmatic, technical and training aspects of oxygen systems.

- Communication and cooperation must take place at all levels – between the health facilities’ clinical, bioengineering and administrative departments, between the national health department and provincial hospitals, and with outside agencies.

- Building local capacity in maintenance and repair within hospitals and in the health department is vital; relying on local supply agents to service equipment may lead to long delays and high costs. Preventive maintenance is essential, and failure to provide this results in costly repairs and down-time of equipment.

- Technical expertise in procurement, commissioning and installation is important. Machines on the world market vary widely in quality, suitability for hospitals in developing countries and price. Data are available to compare specifications for equipment that is considered suitable for health facilities in developing countries (see http://www.rch.org.au/cich/links/index.cfm?doc_id=699).

- The equipment used should be as uniform as possible, to ensure compatibility of spare parts and to limit confusion among health workers and engineers.

- A high-dependency area should be available within the hospital where oxygen can be given and nurses are nearby. This helps to group together the sickest patients in the one place.

- On-site training should be provided for nurses, doctors and hospital engineers when equipment is being installed in hospitals. Such training takes 1–2 days, and should be reinforced by regular in-service training from an oxygen team. Repeated in-service training is especially important in countries with high staff turnover.

- Simple guidelines should be provided on the clinical use of oxygen and on the regular preventive maintenance of oxygen concentrators and other equipment.

- When giving oxygen to children, it is important to educate parents about the need for oxygen and the function of the components to give them confidence in the treatment. (To learn more about parent education, see section 6.2.5.)

- Oxygen can cause a fire to spread rapidly, and appropriate safety measures need to be in place. Oxygen cylinders are large heavy objects that can be very dangerous if they fall over; they should be installed securely using a cylinder bracket, strap or chain to fix them to the wall. To learn more about safety related to oxygen use, see Chapters 9 and 12, and Annexes A and C.
3.3 Working together to provide a sustainable oxygen system

To implement and maintain an effective oxygen system requires good cooperation and communication between individuals and departments. The system relies on three professional groups: clinicians who recognise and treat patients with hypoxaemia, engineers who keep the equipment running and administrative officers who ensure an ongoing supply and availability of spare parts. Mutual understanding of the respective areas of work and competencies of all concerned is crucial to ensure the smooth running of the oxygen supply system.

Whether you are a doctor, a nurse, an engineer, a technician, a programme manager or an administrator, it is important not to be discouraged when difficulties and obstacles are encountered, especially at the beginning. Properly implementing and maintaining a new oxygen system is a large undertaking, and progress takes time. Some things will be outside your direct control, and you may need to talk to others to influence these. However, in many countries, despite imperfect and fragile health services, patients’ lives are being saved by steady and incremental improvements brought about by such programmes, and overall quality of care is improving.

Figure 3.1 A effective oxygen system requires a reliable method for detecting hypoxaemia and an uninterrupted supply of oxygen
Part II  Detailed information for different professional groups
Section A Information for clinicians

KEY MESSAGES

- Oxygen systems are needed in all areas where seriously ill patients are managed: paediatric ward, adult medical, surgical and obstetric wards, operating theatre and emergency department.

- During triage in outpatient or emergency departments, all patients should be checked for emergency and priority signs, which include clinical signs of hypoxaemia. Patients at high risk of hypoxaemia (e.g. those with respiratory infections) should undergo pulse oximetry. Patients with emergency or priority signs or with suspected hypoxaemia should undergo pulse oximetry.

- In inpatient settings, pulse oximetry should be performed on all patients at the time of admission.

- Any patient with SpO₂ <90% on pulse oximetry or clinical signs of hypoxaemia should receive oxygen. For some conditions it is appropriate to give oxygen when the SpO₂ is <94%.
4 Hypoxaemia

This chapter gives a more advanced definition of hypoxaemia and briefly outlines age-specific conditions that commonly cause hypoxaemia.

4.1 Definitions of hypoxaemia and thresholds for giving oxygen

The range of means for haemoglobin oxygen pulsed saturation (SpO₂) at sea level is 97–99%, with the lower limits (mean – 2 SD) being 94%. Therefore, the normal range at sea level is 94–100%. The normal range of SpO₂ becomes progressively lower in populations living in mountainous regions, because of lower PaO₂ at higher altitude (see Figure 4.1). This was estimated using data from 16 studies in children outside the neonatal period. The continuous line predicts the level of SpO₂ below which oxygen should be given at different altitudes.

![Figure 4.1 Threshold of hypoxaemia at different altitudes](image)

Changing the point at which hypoxaemia is defined and oxygen is given results in a major variation in the amount of oxygen used. A report from one hospital found that 13% of children with pneumonia were hypoxaemic using a definition of SpO₂ <85%, 26% were hypoxaemic using SpO₂ <90% and 44% were hypoxaemic using SpO₂ <93%.

The best cut-off point for giving supplemental oxygen may be the level of blood oxygen that is associated with increased morbidity or risk of death or delayed recovery, rather than a certain level of haemoglobin oxygen saturation below normal for the population. With normal cardiac output, haemoglobin concentration and pH, arterial oxygen saturations of 68% or more are probably not dangerous. However, there are few data about the exact SpO₂ below which the risk of adverse outcomes increases. This risk will be different for different ages, disease states, comorbidities and at different altitudes, and a safe margin for error is required.
The gold-standard measure for the oxygen content of the blood is the arterial oxygen tension or PaO₂ (measured in mm Hg or kilopascals). PaO₂, however, can only be measured by blood gas analysis. This method is invasive, painful and distressing to the patient, and blood gas machines and reagents are very expensive and, therefore, not appropriate in most district hospitals in developing countries. Therefore, we use SpO₂, which is related to PaO₂, to define hypoxaemia in these guidelines (see Figure 4.2).

In practice, most studies have adopted a threshold at which to give oxygen of SpO₂ <90%. This corresponds to the beginning of the steep part of the haemoglobin–oxygen dissociation curve, which is shown in Figure 4.2. Small reductions in SpO₂ below 90% may represent dangerous falls in PaO₂. This represents a safe margin for error where oxygen supplies are sufficient.

It is important to note that small changes in SpO₂ between 90% and 100% reflect large changes in PaO₂, because the haemoglobin–oxygen dissociation curve is relatively flat. Below an SpO₂ of 90%, however, the curve is steep and small falls in PaO₂ may result in much larger falls in SpO₂.

There will be conditions that require oxygen therapy at higher thresholds than 90% SpO₂. These are conditions where oxygen delivery from the lungs to body tissues is seriously impaired, or where vital organs may be particularly susceptible to low oxygen levels. Examples include severe anaemia, severe heart failure, severe sepsis or brain injury. In these conditions, many clinicians recommend giving oxygen if the SpO₂ is <94%.

![Figure 4.2 Haemoglobin–oxygen dissociation curve](image)
4.2 Definition and causes of hypoxaemia in neonates

It is important to note that newborn infants, particularly preterm babies, have lower normal oxygen saturations than infants after the first week of life. Normal levels for newborns are typically 86% or above. Therefore, the aims of oxygen therapy need to reflect this.

A number of conditions that may lead to hypoxaemia occur only, or at higher frequency, in neonates, notably respiratory distress syndrome, birth asphyxia and transient tachypnoea of the newborn. Pneumonia is also very common. Neonates who are very unwell for reasons such as prematurity, sepsis, seizures or hypoglycaemia are also prone to apnoea. Apnoea and hypoventilation also occur in otherwise-well babies of very low birth weight (weight <1.5 kg or gestational age <32 weeks) because of immature respiratory drive (apnoea of prematurity). Apnoea can lead to hypoxaemia and slowing of the heart rate (bradycardia), further reducing oxygen delivery to tissues.

4.3 Causes of hypoxaemia in children

Since hypoxaemia is an important complication of severe illness and a predictor of death, a significant amount of data is now available on frequency of hypoxaemia in sick children. The data were collected from more than 16,000 children from 21 studies in 13 developing countries.

4.3.1 Acute respiratory infections

Hypoxaemia is a common complication in acute lower respiratory infection (ALRI) in children and is a strong risk factor for death. The most common serious ALRIs are pneumonia and bronchiolitis; these account for most children with hypoxaemia in developing countries. In studies of ALRI requiring hospitalization using the WHO clinical classification (severe and very severe pneumonia), the median hypoxaemia prevalence is 13% (range 9–38%). The hypoxaemia prevalence rates are much higher in some hospitals; some rates exceed 50%.

It has been estimated that 11–20 million children with pneumonia are admitted each year to hospitals. There are, therefore, at least 1.5–2.7 million cases of hypoxaemic pneumonia presenting to health facilities annually. Countless more do not access health care.

Pneumonia in children is most commonly due to bacteria (*Streptococcus pneumoniae* and *Haemophilus influenzae*) and viruses (respiratory syncytial virus, influenza virus). Other pathogens are common in certain high-risk groups, including malnourished children, neonates and children with human immunodeficiency virus. These pathogens include *Staphylococcus aureus*, enteric Gram-negative bacilli (such as *Escherichia coli*, *Klebsiella* species), *Pneumocystis jiroveci* (formerly *Pneumocystis carinii*) and *Mycobacterium tuberculosis*. Hypoxaemia can be a complication of pneumonia from any of these common causes, depending on the severity. Epidemics of influenza are a potential risk in coming years, and effective oxygen systems will be needed in all countries if the management of influenza epidemics is to be effective.

The prevalence of hypoxaemia is generally higher in referral hospitals than in primary care settings, because more severely ill children are referred. Hypoxaemia is also more common at higher altitude, in younger ages and seems to be more common in certain geographical regions.
4.3.2 Other conditions in children

Hypoxaemia also occurs in some children with non-ALRI illnesses such as acute asthma, meningitis and sepsis, but is less frequent than in ALRI. Asthma is an increasing problem globally, especially where urbanization is increasing and among middle-class populations. One study found that 26% of 51 children presenting to an emergency department in India with asthma had hypoxaemia.20

Even conditions that are infrequently complicated by hypoxaemia, such as malaria (where 3–5% of all hospitalized cases have hypoxaemia), can contribute substantially to the global hypoxaemia burden because they are so common.2

4.4 Causes of hypoxaemia in adults

The predominant causes of hypoxaemia in adults are COPD, acute asthma and pneumonia. As in children, pneumonia is most commonly caused by *Streptococcus pneumoniae*. Another major cause of hypoxaemia is influenza. Epidemics or pandemics of influenza are likely in coming years, and part of pandemic preparedness will be to ensure countries have effective oxygen systems. Hypoxaemia also occurs in sepsis, shock, major trauma, anaphylaxis, acute heart failure, pulmonary embolism, pleural effusion, pneumothorax, lung fibrosis, carbon monoxide poisoning, obstetric and surgical emergencies, and in sickle cell crises. Women who suffer sepsis or acute complications of pregnancy are prone to hypoxaemia. To learn more about oxygen therapy for adults in these conditions, see Chapters 6 and 7.

**KEY MESSAGES**

- Hypoxaemia is a common complication in acute lower respiratory infection (ALRI) in children, and is a strong risk factor for death.
- At least 13% of children presenting to hospitals with severe or very severe pneumonia have hypoxaemia, and the rates are much higher in some hospitals; some exceeding 50%.
- The prevalence of hypoxaemia is higher in referral hospitals than in primary care settings. Hypoxaemia is more common at higher altitude, in younger ages and in certain geographical regions.
- Hypoxaemia occurs in some children with illnesses other than acute respiratory infection, such as acute asthma, meningitis, sepsis and malaria.
- Sick neonates are at risk of hypoxaemia, because several conditions, such as respiratory distress syndrome, apnoea, birth asphyxia and pneumonia are common.
- SpO₂ <90% is the most clinically useful definition of hypoxaemia and is considered by most clinicians as an appropriate indication for giving oxygen.
- In some clinical situations it is more appropriate to give oxygen to patients with an SpO₂ of <94%. These include severe anaemia, cardiac failure and brain injury.
- Preterm infants (<32 weeks gestation) are at risk of oxygen damage to the eyes; aim to keep SpO₂ between 85% and 95%, but not higher.
- COPD, asthma, pneumonia, trauma, and obstetric and perioperative emergencies are common causes of hypoxaemia in adults.
5 How to know if a patient needs oxygen

Clinicians can detect hypoxaemia using clinical signs, pulse oximeters or blood gas analysis. This chapter outlines these methods, and explains the advantages and disadvantages of each.

5.1 Clinical signs of hypoxaemia

As explained earlier, clinical signs are not a very reliable predictor of hypoxaemia, and using these alone for diagnosis may lead to false positive or false negative results. However, in many situations, such as primary health facilities or triage in an outpatient or emergency department, it may not be possible to perform pulse oximetry. When looking at the clinical appearance of a patient, different signs are indicative of hypoxaemia in neonates, children and adults. It is very important for health workers to have the skills to identify very sick patients clinically, and to identify the clinical signs of hypoxaemia, rather than to rely on monitoring equipment that might not be available or functioning, and also has inaccuracies.

5.1.1 Clinical signs of hypoxaemia in neonates

Signs of hypoxaemia are less specific in neonates and younger infants, and this may lead to delayed recognition by parents and presentation at a relatively advanced stage. Even for an experienced health worker it may be difficult to detect hypoxaemia.

As with older infants and children (see next section), there is no one clinical sign that identifies all hypoxaemic neonates. Several studies have shown that in neonates, as in infants and children, fast breathing is both insensitive (i.e. many children with hypoxaemia may not have fast breathing) and nonspecific (i.e. many children with fast breathing are not hypoxaemic) for detecting hypoxaemia. As in older children, cyanosis is the most specific clinical sign for detecting hypoxaemia in neonates, but more than one quarter of neonates with hypoxaemia will not be identified as being cyanosed. A sensitive combination of clinical signs of hypoxaemia is central cyanosis (blue discolouration of the normally pink mucous membranes of the gums or tongue) or a respiratory rate of >60 breaths/minute or not feeding. However, the low specificity of some of these signs means that almost half the infants who fulfil these criteria will not need oxygen. Where pulse oximetry is not possible, the combination of central cyanosis or respiratory rate of >60 breaths/minute or not feeding will detect about 90% of infants with hypoxaemia, but will result in the unnecessary use of oxygen in many infants.

These considerations argue strongly for the use of pulse oximetry in the management of sick neonates, and the importance of teaching health workers to screen for these common clinical signs. Where available for inpatient monitoring of very low-birth-weight babies and premature neonates, apnoea monitoring is also recommended.
5.1.2 Clinical signs of hypoxaemia in children

This section describes the clinical signs that suggest hypoxaemia in children. The precision of these clinical signs in predicting hypoxaemia have been reviewed.8;21

Central cyanosis

Oxygenated haemoglobin is red, while deoxygenated haemoglobin is blue. If the red cells in the blood are not fully loaded with oxygen, the skin and mucous membranes appear blue rather than pink. This is known as central cyanosis (see Figure 5.1).

Note: In this figure, the SpO2 is 66% and the pulse wave trace is good, confirming severe hypoxaemia. The infant should be given oxygen urgently.

Figure 5.1 Child with central cyanosis and chest indrawing

Identification of central cyanosis can be difficult. Examine the tongue or gums (not the lips) under sunlight or the light from an incandescent light bulb (even healthy people may look slightly blue under fluorescent light). If unsure, compare the colour of the child’s tongue with that of the mother’s. Blue discolouration of the nail-beds or lips only indicates peripheral cyanosis, which can occur with intense vasoconstriction as a result of hypothermia, exposure to low environmental temperatures or circulatory shock. Sometimes peripheral cyanosis will occur without hypoxaemia.

Among children with severe anaemia and in those who have heavily pigmented mucous membranes, cyanosis may only be easily detectable at severe levels of hypoxaemia.6 Central cyanosis has poor sensitivity for accurate detection of hypoxaemia; that is, of all children with hypoxaemia, central cyanosis will be detectable in less than 50%. However, central cyanosis has high specificity for detection of hypoxaemia: virtually all children with central cyanosis have hypoxaemia and should therefore receive oxygen.8

Increased respiratory rate

An increase in respiratory rate (>70 breaths/minute in children of 2 months to 5 years) is a physiological response to hypoxia, but respiratory rate is affected by age, 22,23
malnutrition, altitude, and presence of anaemia or fever. It is best measured by observing the movement of the chest wall over a 60-second period.

Studies suggesting increased respiratory rate as a useful indicator of hypoxaemia tend to be at high altitude. At sea level it can be a poorer predictor, and the results depend on the cut-off point selected. Using a higher cut-off, fewer children will be identified, but a higher proportion of these will have hypoxaemia. In most circumstances, tachypnoea alone (without other signs of severe respiratory distress or hypoxaemia) is not a useful indicator for oxygen therapy.

**Coma, severe lethargy, prostration or prolonged convulsions**

Coma or prolonged convulsions (convulsions lasting more than a few minutes) put a child at significant risk for hypoxaemia. Coma or prolonged convulsions may be associated with depression of respiratory drive leading to hypoventilation, or may compromise airway protection and lead to aspiration. However, coma is a nonspecific sign of hypoxaemia: many children with long-standing coma are not hypoxaemic. All children with coma should be examined closely for other clinical signs indicating hypoxaemia (cyanosis, chest indrawing) or airway obstruction (stridor) and given oxygen if there is any uncertainty. Children with coma because of an acute illness (such as meningitis, trauma, cerebral malaria), and children with prostration or prolonged convulsions should receive oxygen immediately. As well as giving oxygen, it is vital to ensure a patent airway, protect the airway from further compromise (such as aspiration) and ensure breathing (ventilation) adequacy.

**Severe lower chest indrawing**

Chest indrawing is the inward movement of the lower chest with inspiration (see Figure 5.2). This is sometimes called subcostal recession, intercostal recession or sternal retraction. Because chest indrawing is a key sign in the diagnosis and classification of pneumonia, most children hospitalized with pneumonia will display it to some degree. It is therefore difficult to quantify the usefulness of severe indrawing in predicting hypoxaemia. However, in the absence of pulse oximetry to clarify whether hypoxaemia is present, children with this sign should be classified as having severe respiratory distress and receive oxygen. Where oxygen supplies are limited do not use chest indrawing alone as a sign to give oxygen.

![Figure 5.2 Severe lower chest wall indrawing indicates that this child needs oxygen](image-url)
Head nodding, grunting or nasal flaring

Grunting on expiration with every breath and nasal flaring are important signs of severe respiratory distress, especially in infants, and indicate the immediate need for oxygen.

Head nodding is when the head nods downwards towards the chest each time the child breathes in; it is a result of the use of accessory muscles in breathing. There are limited data evaluating the usefulness of this sign. Two studies in the same site found that most children with this sign are hypoxaemic. However, many hypoxaemic children do not have this sign.29,31

Crepitations or crackles

Crepitations or crackles are abnormal respiratory sounds that can be heard with a stethoscope. They are the sound of air passing through fluid in the respiratory tract (either the bronchi or alveoli). Several studies have found this sign to be significantly associated with hypoxaemia, particularly in younger age groups.22,31-34 However, it may be difficult for staff without training in the use of a stethoscope to distinguish this sound.

Inability to drink

In a young infant, inability to feed means breastfeeding or bottle-feeding less than half the usual amount. In an older child, it usually means not being able to drink at all. This includes the infant or child who is too weak to drink when offered fluids, who is unable to suck or swallow, or who vomits repeatedly and keeps nothing down. Although breastfeeding children may have difficulty sucking when their noses are blocked, if they are not severely ill they can still breastfeed when their nose is cleared; this should not be classified as “inability to drink”. Inability to drink is a nonspecific sign of hypoxaemia: less than half the children with this sign have hypoxaemia.

5.1.3 Clinical signs and symptoms of hypoxaemia in adults

Hypoxaemia in adults presents as an acute, serious illness in an otherwise well person, or as an acute deterioration in an adult with a chronic condition. Any case of acute breathlessness should alert clinicians to the possibility of hypoxaemia. Dyspnoea or difficult breathing on minimal exertion, inability to talk in sentences, fast respiratory rate, prominent use of accessory muscles to breathe, central cyanosis, chest crackles, tachycardia, restlessness, drowsiness or confusion may be found in adults with hypoxaemia.
KEY MESSAGES

- Where oximetry is not available, clinical signs provide useful criteria on which to base decisions as to who needs oxygen. Oxygen should be given to children with any of the following signs: cyanosis, respiratory rate >70 breaths/minute, severe chest indrawing, head nodding, grunting, severe crepitations, acute coma or inability to feed.

- In addition to respiratory signs, oxygen is indicated for children with prolonged convulsions or other causes of acute coma. Such acute neurological problems may be associated with hypoxaemia because of an obstructed airway or impaired ventilatory effort. Therefore, as well as giving oxygen, it is vital to ensure a patent airway, protect the airway from further compromise (such as aspiration) and ensure breathing (ventilation) adequacy.

- Oxygen may be also required in children with very severe anaemia before a blood transfusion.

- Where possible pulse oximetry should be used in hospitals for the accurate detection of hypoxaemia.
5.2 Pulse oximetry – clinical use, alarms and sensors

A pulse oximeter measures oxygen saturation of haemoglobin in the blood by comparing absorbance of light of different wavelengths across a translucent part of the body. Pulse oximetry is the best method available for detecting and monitoring hypoxaemia.

5.2.1 Clinical use

Even the best combinations of clinical signs commonly misdiagnose hypoxaemia in some patients with normal oxygen saturation, or fail to detect some hypoxaemic patients. Pulse oximetry has been found to correctly identify 20–30% more children who have hypoxaemia than will be found using clinical signs alone.\(^{16,29,31}\) When used correctly, pulse oximetry provides reliable monitoring with little or no distress to the patient; in industrialized countries it is the accepted standard for detecting hypoxaemia.\(^{35}\)

As not all patients with signs sometimes associated with hypoxaemia (such as inability to drink in children) will have hypoxaemia, the use of oximetry can also reduce unnecessary oxygen use. In this way, pulse oximetry can ensure the most efficient use of an expensive resource. The technology is robust and the price of oximeters is now lower than in the past. Pulse oximetry may be a highly cost-effective intervention in hospitals that care for large numbers of children with acute respiratory disease.\(^{36}\)

In the following paragraphs, we describe how pulse oximetry can be used to obtain reliable results in an efficient manner.

Oximetry should be done on all patients who are admitted to the inpatient ward with respiratory illness, emergency signs or any signs of hypoxaemia.

One way to select patients at the time of triage is to screen by oximetry all patients with clinical signs of hypoxaemia, or children and neonates with any “emergency or priority” signs (see box text below).\(^{37}\) This will identify patients most likely to be hypoxaemic.

Where only one oximeter is available in a ward of a district hospital, it is best to use it in the inpatient ward to screen all patients on admission. This way the pulse oximeter will also be available to monitor inpatients.

<table>
<thead>
<tr>
<th>Emergency signs of hypoxaemia</th>
<th>Priority signs of illness</th>
</tr>
</thead>
<tbody>
<tr>
<td>There are a number of emergency signs to be aware of, including:</td>
<td>Priority signs that must also be recognized are:</td>
</tr>
<tr>
<td>• obstructed breathing</td>
<td>• tiny baby, or any sick child aged under 2 months</td>
</tr>
<tr>
<td>• severe respiratory distress</td>
<td>• temperature (child who is very hot)</td>
</tr>
<tr>
<td>• central cyanosis</td>
<td>• trauma or other urgent surgical condition</td>
</tr>
<tr>
<td>• signs of shock (cold hands; capillary refill longer than 3 seconds; weak, fast pulse)</td>
<td>• severe pallor</td>
</tr>
<tr>
<td>• coma</td>
<td>• poisoning</td>
</tr>
<tr>
<td>• convulsions</td>
<td>• severe pain</td>
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<tr>
<td></td>
<td>• respiratory distress</td>
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<tr>
<td></td>
<td>• major burns</td>
</tr>
<tr>
<td></td>
<td>• malnutrition (visible severe wasting)</td>
</tr>
<tr>
<td></td>
<td>• urgent referral</td>
</tr>
<tr>
<td></td>
<td>• oedema of both feet</td>
</tr>
<tr>
<td></td>
<td>• restlessness, continuous irritability or lethargy</td>
</tr>
</tbody>
</table>
Note: The SpO₂ is 88%; this infant should be treated with oxygen.

Figure 5.3  A nurse checks an infant for hypoxaemia using pulse oximeter on admission
5.2.2 Oximeter features

Alarms

A low-battery alarm is essential to alert health workers when the machine needs to be plugged into a power supply (AC mains). It is very important that the oximeter is connected to mains power whenever it is not being used around the ward. If the internal battery discharges, the oximeter will only work if plugged into the mains, and its utility as a portable monitoring tool will be limited.

Sensors

There is a wide range of digital probes available. Some are disposable, but can be reused on several patients over a week or more until the infrared light signal fades. However, these are difficult to clean and the adhesive wears off after a few uses. There are several types of longer life digital probes that are more expensive. For adults there are hard plastic finger clips; these will not attach well to infants or children (Figure 5.4).

![Figure 5.4 Hard plastic finger clips for adults](image)

One type of probe used for a wide range of patient ages and sizes is a device with a soft rubber pocket (Figure 5.5). Because the casing is soft, the probe will generally mould to the digits of children and adults. These soft probes are ideal for spot checks and daily monitoring, as they do not need adhesive to attach. Probes and the connecting cables are delicate and easily become damaged if stepped on. With proper care a single, soft, digital probe can be used on many hundreds of children, and there is experience from developing countries that even with heavy use they have a usable life span of about a year.

![Figure 5.5 Soft rubber probe](image)

Another alternative is the “Y-sensor” probe, but these require some form of attachment to the hand, foot, toe or finger (Figures 5.6). These can be ideal for neonates and young
For very low-birth-weight neonates, these soft, digital probes can be attached to the foot or hand.

Figure 5.6  Y-sensor probes

It is important always to have a spare probe available in case one fails. Some probes are designed to attach to the ear lobe, but generally these have less applicability across various ages, and for spot checks and daily monitoring.

Examples of pulse oximeter displays showing normal or abnormal readings are described below.

Figure 5.7 shows a pulse oximeter with a normal reading (pulse rate = 102 beats/minute; SpO₂ = 97%) and a plethysmographic (pulse) wave indicating a good arterial trace and a valid reading.

Figure 5.7  Pulse oximeter showing a normal reading
An abnormal pulse oximeter reading is shown in Figure 5.8, taken from a 6-year-old child (pulse rate = 55 beats/minute; SpO₂ = 83%). In this case, the plethysmographic (pulse) wave is uneven, indicating a poor arterial trace. The accuracy of the heart rate reading should be checked by comparing the number on the oximeter display with auscultation of the heart and counting the true beats. In this case, auscultation revealed the true heart rate was 120 beats/minute. A poor pulse waveform on the oximeter, as in this case, usually occurs because of poor connection of the sensor probe to the skin, especially in an active child, or because of poor peripheral perfusion. This SpO₂ reading is not valid, and the probe would need to be repositioned.

![Figure 5.8 Pulse oximeter showing a poor plethysmographic (pulse) wave](image)

In Figure 5.9 (pulse rate = 150 beats/minute; SpO₂ = 82%), however, the pulse oximeter has a good plethysmographic wave, indicating a valid arterial trace. Therefore, the SpO₂ reading, which is abnormally low (82%), is accurate and indicates the patient has hypoxaemia. Oxygen should be given. Note the increased heart rate, which is common in seriously ill patients.

![Figure 5.9 Pulse oximeter showing a good plethysmographic (pulse) wave and low oxygen saturation](image)
KEY MESSAGES

- If oximetry is available only at the time of admission, screen all patients if time allows, or those patients with any clinical signs of hypoxaemia, including all children with emergency or priority signs.

- If oximetry is used at outpatient triage, screen all children with any emergency or priority signs.

- Any child with an SpO₂ <90% should receive oxygen.

- All adults with breathlessness or any signs of respiratory or cardiac disease should be screened with pulse oximetry, and oxygen given if the SpO₂ is <92%.

- In some patients, particularly those with severe anaemia, heart failure or shock, oxygen should be given if the SpO₂ is <94%.

- For some children living at high altitude (e.g. >2500 m) it will be appropriate to give oxygen when the SpO₂ is <85%.

- Use oximetry, at least daily, to check any patients who are already on oxygen, and screen any patient who develops any emergency signs or shows other clinical signs of deterioration.

- Explain the meaning of oximetry to parents. This will help them understand the importance of oxygen and other treatments and will involve them in their child’s care.

- In patients receiving supplemental oxygen, pulse oximetry cannot be used to monitor the adequacy of ventilation.

- Children should not be discharged until their SpO₂ has been stable at 90% or more while breathing room air for at least 24 hours, until all emergency and priority signs have resolved, and until appropriate home treatment can be organized.
5.3 Blood gas analysis

Blood gas analysis measures the PaO₂ and carbon dioxide in arterial (or venous or capillary) blood. Blood gas analysis also provides information about blood pH, which is often abnormal in seriously ill patients. Metabolic acidosis (low blood pH) is commonly seen when there is major disturbance of the circulation, as in severe dehydration, severe sepsis and severe malaria. Thus, blood gas analysis provides information on oxygenation, ventilation and circulation. Electrolyte concentrations (particularly sodium and potassium) are also measured using the same blood sample and analyser. Electrolyte abnormalities are very common in seriously ill patients.

Blood gas analysis has several drawbacks, and in hospitals where resources are limited, blood gas analysers have little or no role. Blood gas analysis is compared with pulse oximetry in Table 5.1.

Blood gas monitoring involves taking arterial blood, and is invasive, painful and distressing to patients, especially to children and infants.

Blood gas analysis provides information at only a single point in time. Without an arterial cannula for repeated sampling of blood, arterial blood gas analysis is rarely a practical means to monitor changes in response to therapy. Venous and capillary blood gases, an easier alternative to arterial monitoring, are of no use for determining oxygenation, and these have other sources of error.

Inaccurate information can easily result from many factors, such as a poorly taken sample (especially from a struggling or uncooperative child), delay in transfer to a laboratory, inadequate storage conditions before analysis and inadequate maintenance or quality control within the laboratory.

Blood gas analysers are very expensive, and the chemical reagents are a high ongoing cost, which is often unaffordable. There are many examples of blood gas analysers being donated to hospitals in developing countries, only soon to lie idle because the reagents are unaffordable.

Aside from these disadvantages, there is some information that can be gained from blood gases that cannot be gained from pulse oximetry; this is discussed below.

The level of carbon dioxide in the blood assesses the efficiency of ventilation. Although arterial blood provides the best information on alveolar ventilation, arterialized capillary blood or even venous blood can be of some value in identifying major changes in ventilation, and in monitoring trends.

The pH provides a direct assessment of overall acid–base status (from arterial, arterialized capillary and venous blood). The likely cause of pH disturbances can only be inferred from examining the partial pressure of carbon dioxide and blood bicarbonate concentration (and/or the base excess or deficit). In sick children in developing countries, metabolic acidosis is the commonest pH abnormality; occurring in severe sepsis, severe diarrhoea with dehydration and severe malaria. In each of these conditions metabolic acidosis is an indication of dehydration, hypovolaemia or shock. Metabolic acidosis occurs also in the less common but important condition of diabetic ketoacidosis, where acidosis is predominantly due to the accumulation of ketone bodies. Metabolic acidosis also occurs in some poisonings with acidic compounds, such as in aspirin overdose and ethylene glycol ingestion, as well as in carbon monoxide intoxication.
Table 5.1 Comparison of pulse oximetry and blood gas analysis

<table>
<thead>
<tr>
<th>Factor to be considered</th>
<th>Pulse oximetry</th>
<th>Arterial blood gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain and distress to patient</td>
<td>Minor discomfort from being held</td>
<td>Very high discomfort</td>
</tr>
<tr>
<td>Risk to staff</td>
<td>Nil</td>
<td>Moderate (potential for needle stick)</td>
</tr>
<tr>
<td>Suitability for monitoring</td>
<td>Continuous or regular spot checks</td>
<td>Single point information only</td>
</tr>
<tr>
<td>Cost</td>
<td>Moderately expensive plus moderate ongoing costs (sensor probes)</td>
<td>Very expensive plus large ongoing costs for reagents and maintenance</td>
</tr>
<tr>
<td>Skill required</td>
<td>Use and interpretation skills can be taught to nurses and non-specialist health workers</td>
<td>High level of laboratory expertise and skill in clinical interpretation</td>
</tr>
<tr>
<td>Indication of ventilation adequacy</td>
<td>Useful information only in children breathing room air No indication in children on supplemental oxygen</td>
<td>Yes</td>
</tr>
<tr>
<td>Indication of metabolic state</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Major sources of error</td>
<td>Poor skin perfusion Movement artefact Wide confidence intervals (greater margin for error) at lower SpO₂</td>
<td>Uncooperative child Clotted specimen Air in syringe Laboratory handling</td>
</tr>
</tbody>
</table>

**KEY MESSAGES**

- Although information from blood gas analysis can be of value, its usefulness is greatly limited in most hospitals in most countries by very high initial and recurrent costs, invasiveness, and the need for trained staff for specimen processing and interpretation of results.
- In the absence of an indwelling arterial line, blood gas analysis requires recurrent painful procedures to provide sequential information. Arterial lines should not be used outside an intensive care unit, because of the high risk of dislodgement and bleeding.
- Pulse oximetry is much cheaper, and not painful or distressing to a child. In seriously ill children, pulse oximetry should be used for intermittent monitoring of oxygenation. Close evaluation of clinical signs will be more appropriate than blood gas analysis for the detection of problems with ventilation and circulation (see section 6.2).
6 Giving oxygen

This chapter contains information on when to give oxygen, how to monitor progress and what to do when oxygen therapy fails. For more information on delivering oxygen, refer to Chapter 7.

6.1 Giving oxygen to neonates

6.1.1 Respiratory depression at the time of birth: neonatal resuscitation

Perinatal asphyxia is manifested as slow or absent breathing, hypotonia (floppiness), cyanosis or pallor, and bradycardia (slow or absent heart rate) at the time of birth. This is commonly measured as a low Apgar score. For the management of perinatal asphyxia, bag and mask resuscitation with air (containing 21% oxygen) may be as effective as using bag and mask ventilation with 100% oxygen. The primary respiratory problem in most cases of perinatal asphyxia is lack of initiation of ventilation or lack of effective ventilation, so the most important intervention is to assist the newborn to take breaths more effectively. A trial of 609 neonates, comparing outcomes of treating with room air or with 100% oxygen, showed that there was no difference in 7-day mortality, neonatal mortality or moderate to severe hypoxic encephalopathy. The time to initiation of first breath was significantly longer in the oxygen group than in those resuscitated with room air. In addition, there are dangers of prolonged exposure to high concentrations of oxygen in premature neonates (e.g. retinopathy of prematurity; see section 6.1.3).

Sometimes perinatal asphyxia (or low Apgar score) is a complication of neonatal pneumonia, aspiration (of meconium, maternal blood or amniotic fluid) or severe respiratory distress syndrome. It is likely that in utero passage of meconium and aspiration of infected liquor is often stimulated by asphyxia, so the primary problem is uncertain. Neonatal pneumonia is often associated with prolonged rupture of membranes or maternal fever, but there may be no preceding known risk factors. In cases of severe neonatal pneumonia or aspiration complicated by low Apgar score, initiating effective ventilation will be necessary. However, this will generally not be sufficient to sustain acceptable oxygenation, and supplemental oxygen will be necessary also.

The first priority for asphyxiated babies, therefore, should be the adequate inflation of the fluid-filled lungs. Attention should then be given to the desired concentration of inspired oxygen. Resuscitation of the newborn is described in detail in the WHO Pocketbook of Hospital Care for Children.

Respiratory depression at the time of birth may occur if the mother has received opiate drugs (morphine or pethidine) during labour. In these cases, giving naloxone by intramuscular injection at a concentration of 0.1 mg/kg, along with bag and mask ventilation, is often effective.
6.1.2 Newborns who remain hypoxic despite oxygen

If a newborn remains hypoxic despite being given oxygen, check that the baby is making adequate efforts to breathe and that the chest is rising and falling. If not, bag–mask ventilation should be given. Check that oxygen is being delivered to the baby: check tubing connections for leakage or try another oxygen source. Cyanosis in newborns will sometimes be due to heart or structural lung problems. An infant who remains cyanosed or has low SpO₂ despite oxygen and is making good efforts to breathe should be reviewed by an experienced practitioner to assess whether there is another reason for hypoxaemia, such as a diaphragmatic hernia, congenital heart disease, pneumothorax or a congenital lung abnormality.

6.1.3 Oxygen toxicity in preterm newborns

Eye damage, called retinopathy of prematurity (ROP), can result from excessive oxygen exposure in very low-birth-weight babies. The highest risk babies are those <32 weeks gestation or <1250 g; the smaller the baby the greater the risk. If pulse oximetry is available, SpO₂ should be maintained above 85% but no higher than 95%, to prevent eye damage. However, ROP can develop even with meticulous monitoring in extremely premature babies with multiple problems. Most mild ROP resolves spontaneously. All babies <32 weeks gestation or <1250 g, and larger, preterm babies who received oxygen should be screened for ROP at 4–6 weeks of age.

6.1.4 Adjunctive therapies to treat apnoea and severe hypoxaemia

Therapies to treat apnoea and severe hypoxaemia in neonates include (methylxanthines) and continuous positive airway pressure (CPAP). Methylxanthines can treat and prevent apnoea in premature neonates. In some hospitals, equipment for bubble-continuous positive airway pressure (bubble-CPAP) or high-flow CPAP by nasal prongs will be available, and is useful for the management of respiratory distress in neonates for whom basic support with oxygen is insufficient.

Methylxanthines

Aminophylline, theophylline and caffeine are methylxanthines, and have several effects on the respiratory system. These include stimulation of the respiratory centre in the brain, and diaphragm contraction. There is encouraging evidence that in premature neonates with apnoea, aminophylline and caffeine are highly effective. These drugs may be more effective than continuous positive airway pressure (CPAP) in preventing the need for mechanical ventilation, and more effective than tactile stimulation in prevention of apnoea. Caffeine is associated with fewer adverse events than aminophylline and is equally effective in the treatment of apnoea in premature newborns.

Most studies of methylxanthines have been conducted in preterm babies, where the predominant pathologies are hyaline membrane disease and apnoea of prematurity. Whether such respiratory stimulants are beneficial for the treatment of apnoea in term babies and older infants has not been established in controlled trials. Aminophylline has, however, been used effectively in young infants with apnoea due to acute viral bronchiolitis.
6.1.5 Continuous positive airway pressure (CPAP)

CPAP is indicated in infants who have respiratory failure, severe respiratory distress or apnoea despite oxygen. A system of CPAP will be available in some hospitals, but is only appropriate when reliable, oxygen systems (described throughout this book) are in place, where staff are adequately trained and close monitoring is assured. CPAP delivers PEEP with a variable amount of oxygen to the airway of a spontaneously breathing patient to maintain lung volume during expiration. CPAP decreases atelectasis (alveolar and lung segmental collapse) and respiratory fatigue, and improves oxygenation.

Bubble-continuous positive airway pressure

Bubble-CPAP is an appropriate method for delivering CPAP, and has been used successfully in some referral hospitals in developing countries.\(^{43-45}\) The bubble-CPAP system consists of three components:

1. Continuous gas flow into the circuit: CPAP requires a source of continuous airflow (often an air compressor). The gas flow rate required for generating CPAP is usually about 5–10 litres/minute. This alone can generate CPAP with a fraction of inspired oxygen (FiO\(_2\)) of 21%, but many neonates require some supplemental oxygen. Therefore, bubble-CPAP also usually requires an oxygen blender that connects an oxygen source (cylinder or concentrator) with the continuous airflow to increase the FiO\(_2\).

2. A nasal interface connecting the infant’s airway with the circuit (Figure 6.1): short nasal prongs are generally used to deliver nasal CPAP. These must be carefully fitted to minimize leakage of air (otherwise CPAP will not be achieved) and to reduce nasal trauma.

3. An expiratory limb with the distal end submerged in water to generate end-expiratory pressure; in bubble-CPAP the positive pressure is maintained by placing the far end of the expiratory tubing under water. The pressure is adjusted by altering the depth of the tube under the surface of the water.

Several commercial bubble-CPAP machines are available (such as the system illustrated in Figure 6.1). These vary in price from several hundred dollars to 10 thousand dollars.

An inexpensive form of bubble-CPAP can be made using standard nasal prongs. The method is shown in Figure 6.2 and 6.3. This system is being used in several hospitals in Asia (Dhaka Children’s Hospital in Bangladesh and elsewhere), and is working well. Gas (oxygen) flow rates of 5 L/min-10L/min are needed for older children with pneumonia. For small neonates, sometimes 3-4L/min is sufficient to generate CPAP. In premature neonates less than 32 weeks it not safe to use pure oxygen, as giving high concentration oxygen can cause retinopathy of prematurity (ROP). In premature infants another source of air flow, such as an air compressor, or an oxygen blender is required. In older infants requiring higher flows to generate CPAP (up to 10 L/min), running off oxygen in cylinders is inefficient. Using a 10 L/min oxygen concentrator is much more efficient (Figure 2.3).
Figure 6.1  A bubble-CPAP circuit connecting to an infant using close-fitting nasal prongs

CPAP, continuous positive airway pressure.

The clinical use of oxygen in hospitals with limited resources
Figure 6.2  An inexpensive bubble-CPAP set up, using modified nasal prongs
start oxygen flow at 5 L/min, look for bubbles in water bottle, increase up to 10 L/min if needed to generate bubbles

tube to let air escape
constant bubbles indicate positive airway distending pressure being generated
water bottle in which expiratory limb is immersed to a depth in centimeters that equals the CPAP pressure

Figure 6.3 Bubble-CPAP using inexpensive modified nasal prongs can also be run using an oxygen concentrator
High-flow CPAP

There is some recent experience with a simpler method of delivering CPAP to newborns using high gas flow (up to 2 litres per kg per minute) through normal nasal prongs. Although PEEP can be generated by this method, it is not as simple as dialling higher flows from an oxygen source such as a cylinder or concentrator; this would be very dangerous. This method requires highly effective humidification to prevent drying of nasal mucosa, which can lead to bleeding and nasal obstruction. A heated humidifier is necessary; an unheated cold water bubble humidifier would not provide adequate humidification.

High-flow CPAP also requires an oxygen/air blender. It is dangerous to give high-flow oxygen to a preterm baby as the fractional inspired oxygen achieved would be very high, increasing the risk of eye damage. Unlike with bubble-CPAP, with high-flow methods it is not certain what pressure is being delivered, and there is a risk of pneumothorax and gastric distension. All methods of CPAP require careful monitoring.
KEY MESSAGES

- For newborns who are not breathing at birth, a self-inflating bag and face mask can effectively provide positive pressure ventilation using room air, but supplemental oxygen can be used for bag and mask ventilation if it is available.
- For infants outside the immediate newborn period who have apnoea or depressed respiratory effort, oxygen should be given, along with respiratory stimulation with bag–mask assisted ventilation (or CPAP if available, see below) until adequate respiratory effort is restored.
- Oxygen should be given to all neonates who have cyanosis or respiratory rate >70 or who are too sick to feed, where pulse oximetry is not available.
- Where pulse oximetry is available, oxygen should be given to neonates with a SpO₂ <90%. The SpO₂ should be maintained above 90% in term newborns. In very premature neonates (less than 32 weeks gestation) the SpO₂ should always be kept below 95% to prevent eye damage.
- For preterm neonates with apnoea, aminophylline or caffeine can be effective treatments for apnoea.
- CPAP will be useful in management of neonates with severe respiratory distress or apnoea in appropriate settings. Effective and safe methods to deliver bubble CPAP are increasingly becoming available. High-flow CPAP shows promise, but needs further evaluation.

6.2 Giving oxygen to children

6.2.1 When to give oxygen

The clinical signs of hypoxaemia have been evaluated in many studies and reviewed. In situations where the oxygen supply is very limited, for children aged over 2 months, provide oxygen according to the priority listing suggested in Table 6.1. Infants aged <2 months with signs of severe respiratory distress (tachypnoea, severe chest indrawing, head nodding or grunting) should be given oxygen because hypoxaemia puts them at greater risk of apnoea and death.

Oxygen should always be given continuously and should not be administered for recurrent short periods of time (such as every hour or two).
Table 6.1  Clinical indications for oxygen therapy

<table>
<thead>
<tr>
<th>Clinical presentation for severe pneumonia with:</th>
<th>Priority for oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central cyanosis</td>
<td>Very high priority</td>
</tr>
<tr>
<td>Decreased consciousness, unresponsiveness or responsive to painful stimuli only</td>
<td>Very high priority</td>
</tr>
<tr>
<td>Head nodding or grunting</td>
<td>Very high priority</td>
</tr>
<tr>
<td>Severe palmer or conjunctival pallor (severe anaemia) with severe lower chest wall indrawing or fast breathing</td>
<td>Very high priority; high priority should also be given to urgent correction of the underlying abnormality (i.e. blood transfusion and/or antimalarials)</td>
</tr>
<tr>
<td>Acute coma or convulsions lasting more than 15 minutes</td>
<td>Very high priority until respiratory effort has returned to normal; also protect airway and ensure adequate ventilation</td>
</tr>
<tr>
<td>Inability to drink or feed</td>
<td>High priority</td>
</tr>
<tr>
<td>Severe chest indrawing</td>
<td>Priority</td>
</tr>
</tbody>
</table>

When monitoring with oximetry, as a general rule any child with an SpO₂ <90% should receive oxygen. This rule best applies to health facilities located between sea level and 2500 m above sea level, and where oxygen supplies are ample (such as when using concentrators) for altitudes higher than 2500 m.

Where there is sufficient oxygen to treat all children with hypoxaemia, it is the practice in some hospitals to give oxygen if the SpO₂ is <93%. Some doctors suggest oxygen should be “discretionary” between an SpO₂ of 90% and 92% and “mandatory” at SpO₂ <90%. There are certainly some children who will benefit more than others from oxygen when the SpO₂ is in the range of 90% to 93%; those with very severe anaemia, severe heart failure, septic shock and acute neurological illness. These children will be less able to withstand moderately low oxygen levels than children with only lung disease.

Because the normal SpO₂ range is lower at higher altitudes it may be appropriate to only give oxygen for an SpO₂ of 85% or less to children living at an altitude above 2500 m, if oxygen supplies are limited (e.g. when using oxygen cylinders and transport difficulties or cost limit supply).46

6.2.2  What to do if the child does not improve or deteriorates after oxygen is given

It is very important that after starting oxygen therapy, the child is checked within 15–30 minutes to see if the treatment is working. In severely hypoxaemic children, correction may not be complete and clinical signs may remain, or the SpO₂ may still be low. This does not mean that oxygen therapy has failed and should be abandoned. Other children will deteriorate rapidly or slowly despite receiving oxygen. There are a number of possible causes for a lack of response.

- Oxygen delivery is inadequate, so check that
  - flow is occurring (hold the tubing close to your face to feel the flow)
  - there are no leaks from oxygen tubing
  - the nasal prongs or nasal catheter are fitted correctly and not blocked
  - the delivery is via an oxygen concentrator, that the concentration of oxygen being delivered is adequate (>85%).
• There are other problems (see the WHO Pocketbook of hospital care for children, Chapter 4), such as
  - pleural effusion; listen with a stethoscope for breath sounds on both sides of the chest, do a chest X-ray
  - pneumothorax; listen with a stethoscope for breath sounds on both sides of the chest, do a chest X-ray
  - upper airway obstruction (e.g. from croup or a foreign body); listen for stridor
  - bronchospasm (e.g. severe asthma); listen with a stethoscope for wheeze
  - cyanotic heart disease or congestive heart failure
  - ventilatory failure; the child’s respiratory effort is inadequate, the child will have slow or shallow breathing and be lethargic (see section 6.2.3, below).

• If nasal prongs are being used at maximum flow (see section 7.1.1) and the child is still hypoxaemic
  - increase the flow rate if using nasal prongs, up to 4 litres / minute in infants or up to 8 litres / min in older children, as long as there is effective humidification
  - sometimes it is useful to give a second source of oxygen, if it is available, via an oxygen mask (ideally with reservoir bag) to increase the fractional concentration of inspired oxygen (see Figure 7.4)
  - if a second source for mask oxygen is not available, a N-P catheter can give a higher fractional concentration of inspired oxygen than nasal prongs (but never use nasal prongs and an N-P catheter together).
  - begin CPAP or consider the need for mechanical ventilation if you have the equipment (see section 6.1.4 and 7.1.1)

### 6.2.3 Monitoring the progress of children on oxygen

In most hospitals the most appropriate form of monitoring will be regular checks with pulse oximetry on children who might need oxygen, those who are already on oxygen, those who have developed respiratory distress and those who show other clinical signs of deterioration. Oximetry can also be used to determine how long children need to be treated with oxygen. In severe pneumonia the duration of hypoxaemia may be anything from several hours to several weeks; the usual time is 2–5 days.\(^{6,47}\) The duration of hypoxaemia may be longer at higher altitudes than at sea level for a similar severity of pneumonia.\(^ {48}\)

Children who are receiving oxygen should be monitored clinically at least twice a day with pulse oximetry. Children in a stable condition and with SpO\(_2\) > 90% should be tried off oxygen once a day to determine if they still require oxygen (see section 6.2.4).

It is important to be aware that pulse oximeters provide no information on carbon dioxide concentration in the blood and thus no direct information on ventilatory efficiency. It is unlikely that a child who has normal oxygen saturation while breathing room air has impaired ventilation. However once oxygen is administered, SpO\(_2\) can be maintained at normal levels despite severe hypercapnoea. In a child receiving supplemental oxygen, oximetry cannot be used to monitor the adequacy of ventilation. For children receiving
oxygen, therefore, clinical monitoring of respiratory effort, respiratory rate and consciousness level is a better guide to the adequacy of ventilation. A child with inadequate ventilation will have slow or shallow breathing and be lethargic.

In a small hospital, any concern over the adequacy of ventilation should prompt efforts to ensure that the airway is clear and protected and that the patient is positioned to facilitate chest expansion (e.g. sitting in a semi-recumbent position of 20–30 degrees, head up to reduce diaphragmatic splinting if there is abdominal distension, passing a nasogastric tube to deflate the stomach). Referral to a high-dependency area or intensive care unit should be arranged if CPAP or mechanical support is available.

All methods of oxygen administration need supervision by trained personnel to detect and manage complications appropriately. A nurse should check every 3 hours that the prongs or catheter are in the correct position and not blocked with mucus, that all connections are secure, that the oxygen flow rate is correct, that the airways are not obstructed by mucus and that there is no gastric distension. Prongs or catheters should be removed and cleaned at least twice a day.

All severely ill children need regular monitoring of vital signs and general condition. Many deaths in hospitals occur overnight, often when monitoring is infrequent or absent. SpO₂ is the most vital of clinical signs, so pulse oximetry is an invaluable, routine monitoring tool.

For more details on what to monitor and how often, see section 6.2.5 and Annexes A and B.

6.2.4 Trials off oxygen and when to stop oxygen

At least once each day, children in the ward who are clinically stable (have no emergency signs and SpO₂ >90%) should be disconnected from oxygen for 10–15 minutes, and carefully examined for changes in clinical signs and SpO₂, to assess whether supplemental oxygen is still required. Trials off supplemental oxygen are best done first thing in the morning, when there is likely to be adequate staff to observe the child throughout the day. If trials off supplemental oxygen are started in the late afternoon, low staff numbers overnight and the oxygen desaturation that sometimes occurs during sleep mean that there is a risk of hypoxaemia developing unrecognized overnight.

Children who have an SpO₂ <90% while still on oxygen or who are unstable or very unwell should not be given trials on room air.

Before a trial off oxygen, the SpO₂ should be checked to determine if the trial is safe (i.e. SpO₂ >90%). The child should then be disconnected from the oxygen source and observed carefully to avoid any adverse complications of hypoxaemia. If severe hypoxaemia (SpO₂ <80%), apnoea or severe respiratory distress occurs, children should be immediately restarted on oxygen. Some children will become hypoxaemic very rapidly when they are taken off oxygen, and this is a marker of very severe disease and a high risk of death. Parents and nursing staff should be advised to watch the child to see if he/she develops cyanosis or severe respiratory distress.

Where oxygen supplies are ample, children should receive supplemental oxygen until their SpO₂ on room air is 90% or greater. If the SpO₂ is 90% or more after a trial on room air, they should remain off oxygen and the SpO₂ should be rechecked after one hour, as late desaturation can sometimes occur. Any child who appears to deteriorate clinically
should have their SpO₂ checked to determine whether they need oxygen. If bed space allows, children should not be discharged until their SpO₂ has been stable at 90% or more while breathing room air for at least 24 hours, until all danger signs have resolved, and until appropriate home treatment can be organized. This of course does not apply to children with cyanotic congenital heart disease, who have chronic hypoxaemia. For children with right to left intracardiac shunts (such as tetralogy of Fallot) oxygen will not be effective in relieving cyanosis or improving SpO₂.

The chest X-ray appearance does not provide any useful guide to the need for oxygen therapy or when it is appropriate to stop.

6.2.5 General care for children with hypoxaemia or severe respiratory distress

Nursing care of children with hypoxaemia is very important. The following describes the main things to consider, including minimal handling, positioning, fluids and nutrition, and close monitoring.

Minimal handling
Handling can be upsetting to severely ill children, and activity consumes more oxygen. Handling should be gentle, and unnecessary stress or painful procedures should be avoided.

Positioning
Children will often find their own most comfortable position in the bed, or on their mother’s lap, but sometimes their breathing may improve if they are nursed with their head raised about 30 degrees with neck support, rather than lying flat. Some hypoxic neonates and young infants may be more stable in the prone position, as long as their face is not obstructed.

Fluids and nutrition
The following guidelines should be followed when dealing with fluids and nutrition of hypoxaemic children

- Withhold oral feeds while the child has severe chest indrawing or severe respiratory distress because of the risk of aspiration.
- Use an intravenous drip or a nasogastric tube, depending on what can be managed most safely.
- Do not give large volumes of intravenous fluids as this may make the lungs “wet” and worsen hypoxaemia.
- Do not give large nasogastric feeds to children with severe respiratory distress, because the child may vomit and aspirate.
- Make sure that as soon as severe respiratory distress has settled, the child receives good nutrition, preferably breast milk.

Overcoming parents’ concerns about oxygen use

Education of parents about the need for oxygen is important to alleviate fears. Many parents are afraid of oxygen and oxygen catheters. Sometimes they will have seen other children receive oxygen just before they died, and they may fear that the oxygen caused the death. It can be very helpful to show parents the pulse oximeter in operation and
explain to them why the child’s oxygen level is low. It is useful also to show them the clinical signs (such as chest indrawing or cyanosis of the gums or tongue). When oxygen is then applied, parents will see that the SpO2 increases and the child’s respiratory distress lessens. They will have much more confidence in the treatment, and be more likely to accept it. In one hospital in Papua New Guinea, the absconding rate of mothers fell significantly (from about 25% down to 8%) when daily checking of children using pulse oximetry was introduced. This was mostly the result of explanation of the monitoring and its implications (for needing oxygen, needing to stay in hospital or readiness for discharge). It is also a daily demonstration that some special attention is being paid to their child, and mothers appreciate this greatly. Even when illiterate, most of these mothers were still able to understand the significance of the number generated by the pulse oximeter and thresholds for safe discharge when these were explained in their own language.

6.3 Giving oxygen to adults

Hospitals with limited resources should have adequate oxygen supplies and equipment and staff should have sufficient skills and knowledge to manage adults with common medical, surgical and obstetric emergencies.

In adults who are fit and healthy, arterial haemoglobin is almost fully saturated with oxygen (SpO2 95–100%) when breathing room air (where the percentage of inspired oxygen is 21%).

For critically ill adults, high-flow oxygen (6–10 litres/minute) should be administered immediately. Oxygen saturation (SpO2) should be checked by pulse oximetry in all patients who are breathless, drowsy or acutely ill. Oxygen should be prescribed to achieve a target SpO2 of 94–98% in most acutely ill adults, or 88–92% for those at risk of hypercapnoeic respiratory failure (e.g. patients with COPD, morbid obesity, chest wall deformities and neuromuscular conditions).

For patients suffering from tissue hypoxia, increasing the inspired oxygen concentration will improve tissue oxygen delivery while other disease processes are addressed (e.g. giving antibiotics for pneumonia, or bronchodilators for asthma). However, oxygen therapy is only effective if other processes interfering with oxygenation are corrected. For example, a hypoxic postoperative patient with airway obstruction due to the residual effect of anaesthesia drugs will only benefit from oxygen if the airway is opened (using chin lift or jaw thrust). Similarly, a patient who has blood loss from trauma or obstetric-related blood loss will need fluid resuscitation (and if severely anaemic will need blood) to improve the cardiac output and restore oxygen delivery to the tissues.

6.3.1 Giving oxygen in specific conditions in adults

Trauma

In trauma, two phases of tissue and organ injury occur – the initial traumatic impact on the tissues causing immediate physical injury, followed by secondary injury which may result from hypoxia and hypovolaemia. Examples of the primary injury include lung contusion, brain haemorrhage, rupture of spleen or liver, bone fracture or muscle crush injury. The secondary injury exacerbates the primary tissue injury and affects the viability of nearby tissues, causing cellular damage. Toxic chemicals leak out from the damaged cells, further exacerbating the original tissue injury. This secondary injury can be
prevented; for example, treating hypoxaemia and hypotension are the most important factors in the prevention of secondary brain injury after traumatic brain injury.\textsuperscript{49,50}

Traumatized patients may have multiple injuries that result in deficient oxygen transport from multiple causes (Table 6.2). For example, a patient involved in a house fire may have smoke inhalation injury, carbon monoxide poisoning, airway obstruction due to coma, or inadequate gas exchange as a result of rib fractures caused by a fall. A patient involved in a road traffic accident may have an obstructed airway due to coma, impaired gas exchange due to lung contusion, pneumothorax or rib fractures, or inadequate oxygen delivery due to anaemia or hypotension.

<table>
<thead>
<tr>
<th>Pathophysiological problem</th>
<th>Clinical example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low fraction of inspired oxygen (low FiO\textsubscript{2}) or low partial pressure of oxygen</td>
<td>Asphyxiation, drowning, high altitude</td>
</tr>
<tr>
<td>Inadequate ventilation to carry oxygen from the atmosphere to the gas exchange surface in the lungs (alveoli)</td>
<td>Airway obstruction or hypoventilation (e.g. muscle paralysis, opioids or anaesthesia drugs); pneumothorax</td>
</tr>
<tr>
<td>Abnormal alveolar–pulmonary capillary interface, reducing diffusion of oxygen from alveoli to the blood</td>
<td>Drowning, pulmonary oedema, lung fibrosis</td>
</tr>
<tr>
<td>Ventilation/perfusion (V/Q ratio mismatch)</td>
<td>Abnormally high V/Q ratio – pulmonary embolism, hypovolaemia, cardiac failure</td>
</tr>
<tr>
<td>When no perfusion takes place, extra “dead space ventilation” is produced (high V/Q); when no ventilation takes place in a perfused alveolus, “shunting” takes place (low V/Q) – in either situation, blood is not efficiently oxygenated</td>
<td>Abnormally low V/Q ratio – pneumonia, lung collapse or atelectasis</td>
</tr>
<tr>
<td>Inadequate haemoglobin to transfer oxygen</td>
<td>Severe anaemia</td>
</tr>
<tr>
<td>Inability of haemoglobin to bind with oxygen</td>
<td>Carbon monoxide (CO) poisoning (CO binds preferentially to haemoglobin)</td>
</tr>
<tr>
<td>Impaired circulation leading to reduced tissue oxygen delivery</td>
<td>Circulatory shock: sepsis, cardiogenic shock, anaphylaxis</td>
</tr>
<tr>
<td>Cell metabolism unable to use oxygen</td>
<td>Cyanide poisoning, sepsis</td>
</tr>
</tbody>
</table>

The approach to minimizing tissue hypoxia in the traumatized patient is based on airway, breathing and circulation (ABC). The airway is the first priority and must always be maintained. In all significantly traumatized patients, immediate oxygen therapy while the primary survey is carried out is a basic life-saving manoeuvre. Increasing the inspired oxygen concentration reduces the risk of tissue hypoxia while diagnosis and treatment of the underlying injuries is carried out.

Oxygen therapy in major trauma should normally be started at a high concentration, using a variable-performance face mask, preferably with an oxygen reservoir (see section 7.2.2). As the patient is assessed and baseline observations taken, including SpO\textsubscript{2}, the oxygen requirement will be determined and an appropriate flow can be delivered. Primary injury to the lung, such as bruising, bleeding or tearing, is often complicated by decreasing oxygenation over a few hours. Therefore, a normal SpO\textsubscript{2} on admission may change to serious hypoxaemia some hours later.
Perioperative care
There are many reasons why patients are prone to hypoxia in the perioperative period, and oxygen is regarded an essential requirement for safe practice. Some patients are particularly at risk from hypoxia during anaesthesia, such as those with a reduced functional residual capacity (i.e. obese, term pregnancy, lung pathology) and those with difficult airways or increased oxygen requirements (e.g. sepsis, young infants).

Preoperative period
Emergency patients are at high risk of hypoxia from causes such as haemorrhage, hypovolaemia and airway or respiratory problems. Ideally, the surgeon and anaesthetist will have noted this before surgery so that oxygen treatment can begin before transfer to theatre.

Anaesthesia techniques
Various techniques may depress ventilation, lower blood pressure or induce small areas of lung collapse (atelectasis) causing inefficient oxygen delivery during surgery. More importantly, the anaesthetized patient is at risk from periods of apnoea during airway manipulation; for example, during intubation or extubation or from airway obstruction during maintenance of anaesthesia. Administration of 100% oxygen is routine before airway manipulation, and will significantly increase the tolerance to apnoea. Supplementation with 30% oxygen is routine at other times during anaesthesia.

During spinal and other regional anaesthetics, most patients will remain well oxygenated when breathing air unless sedation is used.

Surgery
Surgery may result in hypovolaemia secondary to blood loss that should be treated to guarantee efficient blood flow to the peripheral tissues. Increasing inspired oxygen concentration during periods of rapid blood loss is beneficial.

Oxygen is considered an essential drug in the perioperative period. Detection of cyanosis is particularly difficult under artificial lighting and in patients with dark skin. During anaesthesia, the patient should always be monitored with a pulse oximeter, and additional oxygen administered if the SpO2 is 92% or less.

Recovery from anaesthesia
During recovery from anaesthesia the patient remains under the effect of anaesthetic agents and requires careful supervision and monitoring. The patient is at risk from hypoxia due to airway obstruction (including laryngospasm and poor consciousness state), retained secretions, atelectasis, or increased oxygen consumption due to shivering. Oxygen supplementation should be routine until consciousness returns. Typically this can be provided via a variable performance face mask with 3–6 litres/minute of oxygen.

Postoperative airway obstruction can be masked by high-concentration oxygen, so after anaesthesia patients need to be carefully observed for stridor or other signs of obstructed breathing, and for their consciousness level.

Anaesthesia systems and oxygen supplies
Different designs of anaesthesia systems require varying amounts of oxygen to operate. A drawover anaesthesia apparatus is economical, delivering an inspired oxygen concentration of 35–40% at around 1 litre/minute of oxygen flow, and an inspired oxygen
concentration of around 80% at 5 litres/minute flow. Small oxygen concentrators, which can deliver up to 5–8 litres/minute, can be used with drawover anaesthesia apparatus.

More complex continuous flow anaesthesia machines (plenum machines) are in widespread use, but they rely on a supply of compressed gas, either from cylinders or piped oxygen from an oxygen cylinder manifold, large concentrator or liquid oxygen store. They use several times the flow of the drawover apparatus, but are considerably more economical if used in conjunction with a circle system. Care should be taken in choosing appropriate anaesthetic equipment for the work required and the facilities available.

**Postoperative care**

During postoperative care, especially after major surgery such as laparotomy or thoracotomy, patients are at risk from hypoxia for several days, in part due to atelectasis exacerbated by retained secretions secondary to immobility and pain, or occasionally the excessive use of opioid drugs, which may impair coughing and depress breathing. These complications are particularly likely in elderly patients and patients with chronic lung or heart problems, or spinal deformity. Where facilities exist, it is good practice to administer additional oxygen for 24–48 hours postoperatively to these high-risk patients. Nasal prongs are best tolerated, and 2–3 litres/minutes is ideal. Monitoring SpO2 will guide therapy. Administration of 80% oxygen in the perioperative period (up to 2 hours postoperatively) has been shown to be associated with a reduced incidence of wound infection, but a high concentration of inspired oxygen is not advisable for prolonged periods in the patient with a normal oxygen saturation.

**Obstetric care**

When considering the rational use of oxygen on a pregnant mother, consideration should be given to the well-being of both the mother and the unborn child.

The pregnant mother undergoing caesarean section under general anaesthesia is at risk from hypoxia, especially during induction of anaesthesia, which may be complicated by difficult intubation. The gravid uterus reduces the functional residual capacity (the amount of air in the lungs at expiration) and impairs oxygenation. For 2 minutes before induction of anaesthesia, the mother should breathe 100% oxygen. This will minimize the risk of hypoxaemia on induction. At least 30% oxygen supplementation should be used during maintenance of anaesthesia during elective caesarean section, with the precise level guided by pulse oximetry. The use of oxygen during caesarean section under spinal anaesthesia depends on whether the procedure is elective or emergency, and whether the fetus or the mother may be hypoxaemic. The fetus receives oxygen via the placental circulation. The oxygen partial pressure in placental blood is very low, but fetal haemoglobin binds avidly to oxygen at low partial pressure, enabling efficient oxygen delivery to the fetal tissues under normal conditions. Maternal hypoxia from any cause will compromise the mother and also significantly impair fetal oxygen delivery. During spinal anaesthesia for caesarean section, the mother’s SpO2 should be monitored with a pulse oximeter, and oxygen administered if the level falls below 95%. If the mother is undergoing emergency caesarean section under spinal anaesthesia for fetal compromise, then administration of oxygen to the mother is indicated, even if the mother is not hypoxaemic, as this may help the fetus. However, routine oxygen administration for elective caesarean section under spinal anaesthesia is unnecessary.
Placental hypoxia may occur in the absence of maternal hypoxaemia. When pregnant women lie in the supine position the gravid uterus may press on the inferior vena cava, reducing venous return and cardiac output (aorto-caval compression). This reduces the blood flow to the placenta and subsequently the oxygen supply to the fetus. In addition, the aortic circulation may be compromised resulting in a further reduction of uterine and placental blood flow. Both these events can be prevented by placing the mother in the left lateral tilt position, which shifts the gravid uterus off the major blood vessels.

In any situation where the mother or fetus is compromised, tissue hypoxia is likely to occur and, as with trauma, high-flow oxygen should be delivered in the initial stages while the situation is managed. Maternal haemorrhage, reduced consciousness level with pre-eclampsia or eclampsia, or fetal distress, all benefit from oxygen therapy to prevent further deterioration in fetal oxygenation.

**Sepsis**

Patients suffering from sepsis are common in developing countries. Sepsis occurs from a variety of diagnoses including abdominal, thoracic, renal or gynaecological infections, as a complication of trauma, or postoperative and nosocomial infections. Patients with sepsis suffer a variety of clinical problems including inefficient oxygenation due to acute respiratory distress syndrome, hypovolaemia and inefficient peripheral blood flow resulting in cellular hypoxia. Oxygen is the key in management of these patients, who will require admission to a high-dependency area or an intensive care unit if they develop life-threatening hypoxaemia. Early treatment of the source of the infection (such as drainage of pus), and treatment of any underlying conditions and complications are vital.56

**Chronic obstructive pulmonary disease**

COPD is a common smoking-related lung disease in adults. Hypoxaemia in people with COPD is most common during exercise, during activities of daily living and at night. Hypoxaemia in COPD leads to pulmonary hypertension and secondary heart failure. Acute exacerbations of COPD, leading to hypoxaemia, can occur because of infections or bronchospasm. Adults with COPD with increasing breathlessness should be examined for signs of hypoxaemia and SpO2 should be checked.

About 10% of patients with COPD are vulnerable to repeated episodes of hypercapnoeic respiratory failure (type II respiratory failure). Because their blood carbon dioxide levels are chronically elevated, their brain fails to respond to the rising level, only responding to falling blood oxygen levels. If high-flow oxygen is given, this may remove their hypoxic stimulus to breathe and apnoea or ventilatory failure may occur. In these cases it is recommended that treatment should aim at a target SpO2 no higher than 88–92%. The oxygen dose should be reduced if the saturation exceeds 92%, to avoid hypercapnoeic respiratory failure.57

Quality of life can be improved by long-term oxygen therapy in patients with COPD. Two studies have found a 5-year survival benefit from continuous oxygen therapy in adults with severe hypoxaemia.58
Figure 6.2 In adults with chronic pulmonary disease and hypoxaemia, oxygen therapy can improve their quality of life

6.3.2 Failure to respond to oxygen therapy

When a patient does not respond to oxygen by an increase of SpO2 to normal levels and by a reduction in clinical signs, the oxygen concentration should be increased and a further assessment of the underlying illness made. Some conditions (such as a pneumothorax) may respond to specific treatment. Others, such as a severe pneumonia, may respond to appropriate antibiotic therapy and physiotherapy. Some patients will not improve with these treatments, and will require positive pressure (such as CPAP) or mechanical ventilation in intensive care, which may be available in medium to large units in developing countries.

6.3.3 Adverse effects of oxygen therapy

There are no significant side-effects of breathing oxygen at therapeutic concentrations in acutely ill patients with hypoxaemia, but care should be taken to avoid prolonged and excessive inspired concentrations by monitoring SpO2. Experimentally, healthy adult volunteers who breathe 100% oxygen continuously for more than 24 hours develop chest pain, breathlessness and pulmonary infiltrates on chest X-ray, which have been recognized as features of oxygen toxicity. The deleterious effects of high oxygen levels (hyperoxia) are not fully understood, but are thought to be due to the release of oxygen free radicals. Hyperoxia may promote atelectasis, reduce brain perfusion, reduce cardiac output, reduce uterine perfusion and worsen reperfusion injury following cellular hypoxia. However, breathing up to 80% oxygen for 2 hours postoperatively has been shown to be safe, and to reduce surgical wound infections.

Oxygen therapy should be limited to the minimum level required to avoid hypoxaemia, but in an emergency situation a high concentration of oxygen should be administered to any patient at risk of tissue hypoxia (see Table 6.2). Prolonged breathing of 100% oxygen should be avoided where possible. Care should also be taken when giving oxygen to chronically ill adults at risk of hypercapnoic respiratory failure (COPD or other known risk factors such as morbid obesity, chest wall deformities or neuromuscular disorders).
This section describes the attachments that link the oxygen source (concentrator, cylinder, etc.) with the patient. The various methods and attachments described can be used regardless of whether the chosen source of oxygen is a concentrator or a cylinder.

The major equipment for delivering oxygen (concentrators, cylinders, piped oxygen sources) and other options is described in Chapters 9 and 10.

7.1 Oxygen delivery methods

The methods used to deliver oxygen should be safe, simple, effective and inexpensive. The effectiveness of different methods for delivering oxygen has been reviewed.7;8 Delivery methods requiring low oxygen flows are cheaper, and appropriate where resources are scarce. Some means of oxygen administration are non-invasive (using a face mask, delivering oxygen into a head box, incubator or tent, or holding oxygen tubing close to an infant’s face). Methods involving the insertion of prongs or catheters for a defined distance into the upper airway are considered “semi-invasive”.7 “Non-invasive” methods require high oxygen flow and are inefficient methods of delivery where resources are limited. “Semi-invasive” methods use lower flows, and are therefore more appropriate where oxygen supplies are scarce. Some “semi-invasive” delivery methods have an additional beneficial effect on lung function through production of PEEP. Moderate PEEP production of up to 5 cm H2O, which can be achieved by nasal and N-P catheters can improve oxygenation by itself, in addition to the effect of increased inspired oxygen fraction.9 This kind of PEEP production may also be effective in the management of apnoea (associated with prematurity or bronchiolitis).10 The main complications associated with various oxygen delivery methods are hypercapnoea (from head boxes and face masks when inadequate flows are used), dislodgement (nasal prongs) and catheter or upper airway obstruction or nasal bleeding (N-P catheters, and to a lesser extent nasal catheters).11 Uncontrolled high PEEP production associated with inappropriately high oxygen flows given by prongs or catheters may lead to gastric distension or pneumothorax.

7.1.1 Oxygen delivery methods in newborns, infants and children

Several oxygen delivery methods are available for children (see Table 7.1). Recommended methods include nasal prongs, nasal catheters, N-P catheters, and head boxes, incubators, tents and face masks. Oral catheters have been described, but their use cannot be recommended. This section further describes these methods and things to consider when using them.

For neonates, infants and children the use of head boxes, face masks or incubator and tent oxygen is generally discouraged, as it is wasteful of oxygen and potentially harmful (from carbon dioxide toxicity). For the optimal balance between safety, efficacy and efficiency, nasal prongs are the preferred oxygen delivery method in most circumstances. The use of nasal prongs helps overcome parental resistance and fear among health workers that results partly from unease about inserting a catheter into a sick child. One of the disadvantages of nasal prongs is their cost, which is presently greater than that of catheters.61 This is why nasal catheters are often used in developing countries. If these are
unavailable, even a cut-down nasogastric tube can suffice as a nasal catheter through which oxygen can be delivered.

Nasal prongs are the best method for delivering oxygen to infants and children with croup or pertussis (whooping cough). In these conditions, a nasal or N-P catheter may provoke paroxysms of coughing. However, it must be remembered that the administration of oxygen to children with croup by any method can be dangerous. Oxygen can mask the signs of severe upper airway obstruction in croup that may result in complete airway obstruction if the child is not provided with an artificial airway (tracheal intubation) or given nebulized adrenaline.

**Nasal prongs**

Nasal prongs are a device that ends in two short tapered tubes (about 1 cm in length) designed to lie just within the nostrils (Figure 7.1). They are also called nasal cannulae. There is no risk of gastric distension at standard flow rates, as it is not possible to insert them too far into the nasal passage. Humidification is not required with nasal prongs when using standard oxygen flow rates, as the natural nasal mechanisms heat and humidify the delivered inspired oxygen. There is only a slight risk of airway obstruction by mucus; however, the risk is higher if high flows are used. The actual FiO₂ reaching the patient’s airway is not 100% because of room air entrainment. The FiO₂ therefore depends on the oxygen flow rate, the relation between prong and nasal diameters, and the patient’s body weight (as this partly determines the volume delivered per minute). In infants up to 10 kg in body weight, oxygen flows of 0.5 litre/minute, 1 litre/minute and 2 litres/minute produce FiO₂ values of about 35%, 45% and 55%, respectively. PEEP production with nasal prongs is unpredictable. Achievement of PEEP depends on the distal prong diameter, the oxygen flow and the body weight. Whereas 1 litre/minute oxygen may produce a PEEP of about 5-cm H₂O in premature infants, there is no significant PEEP production with the same flow in infants up to 10 kg in body weight. The maximum flow rate through nasal prongs without humidification is 1 litres/minute in newborns, 2 litres/minute in infants, 4 litres/minute in preschool children and 6 litres/minute in schoolchildren.
Practical considerations

The distal prong diameter should fit well into the nostril (premature infants: 1 mm, newborns up to 10 kg: 2 mm). Prongs need to be secured with a piece of tape on the cheeks near the nose. Care should be taken to keep the nostrils clear of mucus, which can block the flow of oxygen. The maximum flow rate without humidification is 1 litres/minute in newborns, 2 litres/minute in infants, 4 litres/minute in preschool children and 6 litres/minute in schoolchildren. Higher flow rates without effective humidification may cause drying of nasal mucosa, with associated bleeding and airway obstruction. In some hospitals doctors or nurses trim the ends of nasal prongs to make them less troublesome to children, however this may entrain more room air, therefore compromising oxygenation.

Nasal catheters

A nasal catheter is a thin, flexible tube that is passed into the nose and ends with its tip in the nasal cavity (see box below and Figure 7.2). Nasal catheters are usually well tolerated, and they are unlikely to be dislodged. Humidification of the oxygen is not necessary, because the tip of the catheter lies in the nasal cavity. Catheters can become blocked with mucus, and accumulation of mucus can cause upper airway obstruction. The risk of displacement into the oesophagus, with a consequent risk of gastric distension, is small. Ideally, a nasogastric tube should be in place to decompress the stomach if distension occurs. There are no published data on actual FiO₂ values achieved or PEEP production with nasal catheters. Nasal catheters are less efficient in improving oxygenation than N-P catheters, but lead to fewer complications.

Practical considerations

In newborns and infants, 8-French (F) catheters should be used. A catheter passed for a distance that is equal to the distance from the side of the nostril to the inner margin of the eyebrow usually reaches the posterior part of the nasal cavity. In infants, this is about 2.5 cm. The tip of the catheter should NOT be visible below the uvula. The catheter is easily secured with tape above the upper lip. The maximum flow rate should be set at 0.5–1 litres/minute in newborns and 1–2 litres/minute in infants and older children. A nasogastric tube should be in place at the same time (in the same nostril so as not to obstruct both nostrils). Higher flow rates without effective humidification may cause drying of nasal mucosa, with associated bleeding and airway obstruction.
Nasopharyngeal catheters

This catheter is passed to the pharynx just below the level of the uvula (see box below and Figure 7.3). Oxygen delivery by a N-P catheter is the most economic of all the methods described here: better oxygenation is achieved with lower oxygen flows compared with nasal prongs.\(^48\) This is because of the relatively high FiO\(_2\) reaching the trachea and the significant PEEP production: in infants 1 litre/minute of N-P oxygen given using an 8-F catheter produces a PEEP of 2.8-cm H\(_2\)O (SD 2.7).\(^9;64\) However, there are some problems associated with N-P catheters that necessitate close supervision,\(^51\) which means that in most settings where frequent monitoring is difficult, nasal prongs or nasal catheters will be the preferred method, except in children with severe hypoxaemia. N-P catheters are prone to become blocked with mucus, and accumulation of mucus can cause upper airway obstruction.\(^48;65\) Oxygen given through an N-P catheter bypasses the humidifying and warming properties of the nose. Effective external humidification is therefore essential to avoid drying of the pharyngeal mucosa and to reduce the likelihood of thickened secretions blocking the catheter.\(^68\) However, it has been shown that a cheap, unheated bubble humidifier gives acceptable results when low flows of oxygen (0.5–1.0 litres/minute) are given in warm climates.\(^67\) There is a risk that the N-P catheter will be displaced downward into the oesophagus and cause gagging, vomiting and gastric distension. N-P catheter use should be limited to situations where nasal prongs are unavailable, where staff are familiar with the insertion technique and with supervision, where oxygen supply is limited and for children in whom cyanosis or oxygen desaturation is not relieved by oxygen given via nasal prongs or nasal catheter.

Because of the reliable production of moderate PEEP, oxygen administration by a N-P catheter retains a place in the management of patients with severe hypoxia and/or apnoea (associated with prematurity or bronchiolitis). N-P oxygen delivery may be also used in hospitals with very limited oxygen supply, provided that sufficiently trained personnel are available for monitoring and supervision.
A: Measuring the distance from the nose to the tragus of the ear for the insertion of a N-P catheter
B: Cross-sectional view of the position of the N-P catheter
C: Tip of the N-P catheter visible just below the soft palate

Figure 7.3 Nasopharyngeal catheter

Practical considerations

N-P catheters are inserted into the nose to a depth 1 cm less than the distance from the side of the nose (ala nasi) to the front of the ear (tragus). In infants, this distance is about 7 cm. Like nasal catheters, N-P catheters can easily be secured in place with tape. In newborns and infants, 8-F catheters should be used. Maximum flow rate should be set at 0.5 litre/minute in newborns and 1 litre/minute in infants. Higher flow rates without effective humidification may cause drying of nasal mucosa, with associated bleeding and airway obstruction. Because there is a risk of gastric distension with downward dislodgement of the catheter tip, a nasogastric tube should always be in place (passed through the same nostril) to permit rapid decompression of the stomach. The catheter should be removed and cleaned at least twice a day. Humidification is always required. The humidifier should be filled to the correct level with previously boiled, clean water.

Head box, incubator, tent and face masks

Non-invasive methods of oxygen administration have some advantages: with oxygen piped into a head box, incubator or tent, the actual FiO₂ can be precisely determined by an oxygen analyser placed near the baby’s mouth. There is no increased risk of airway obstruction by mucus or of gastric distension. Humidification is not necessary. However, the disadvantages of these methods are of major concern: carbon dioxide toxicity may occur if inadequately low flows of oxygen are used. This can result from setting the oxygen flow too low, or from kinking or disconnection of the oxygen tubing. With a head box, carbon dioxide retention can also be caused by an inappropriately tight seal of the
box around the infant’s neck. A gas flow of 2–3 litres/kg per minute is necessary to avoid rebreathing of carbon dioxide in a head box. Head box, face mask, incubator and tent all require high oxygen flows to achieve adequate concentrations of oxygen and avoid carbon dioxide accumulation, and are therefore expensive and wasteful. Head box and face mask oxygen also interfere with feeding of the child. These methods are not recommended for oxygen administration, especially in settings where oxygen supplies are limited.

**Oral catheters**

The experience with oropharyngeal delivery of oxygen to children is limited and cannot be recommended. Daga et al. described this method. They introduced an 8-F feeding tube through the mouth into the hypopharynx, equal in length to the distance from the side of the nose to the tragus of the ear. The tube was changed once a day. With an oxygen flow rate of 0.5–1 litres/minute they reported adequate oxygenation in preterm babies with respiratory distress and in infants with pneumonia. There were no instances of tube dislodgement or blockage. The authors claim that this method allows unobstructed gas exchange through both nostrils (feeding and oxygen tubes both by the oral route).

Table 7.1 provides a comparison of different methods of oxygen administration.
Table 7.1 Comparison of oxygen delivery methods in children and infants

<table>
<thead>
<tr>
<th>Method</th>
<th>Maximum O₂ flow (litres/minute)*</th>
<th>Actual inspired O₂ fraction (% from 1 litre/minute in 5-kg child)</th>
<th>PEEP</th>
<th>Humidification</th>
<th>Risk of hypercapnoea</th>
<th>Risk of airway obstruction</th>
<th>Equipment required</th>
<th>Nursing demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nasal prongs</td>
<td>Newborns: 0.5–1</td>
<td>45</td>
<td>Minimal</td>
<td>Not required</td>
<td>No</td>
<td>Minimal</td>
<td>Nasal prongs</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Infants: 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preschool: 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>School: 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nasal catheter</td>
<td>Newborns: 0.5</td>
<td>50</td>
<td>+</td>
<td>Not required</td>
<td>No</td>
<td>+</td>
<td>8-F catheter</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Infants: 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nasopharyngeal catheter</td>
<td>Newborns: 0.5</td>
<td>55</td>
<td>++</td>
<td>Required</td>
<td>No</td>
<td>++</td>
<td>8-F catheter, humidifier</td>
<td>+++</td>
</tr>
<tr>
<td></td>
<td>Infants: 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head box, face mask, incubator, tent</td>
<td>Head box: 2–3 litres/kg per minute</td>
<td>Nil</td>
<td>Not required</td>
<td>Yes</td>
<td>No</td>
<td>Head box, face mask</td>
<td>+++</td>
<td></td>
</tr>
</tbody>
</table>

* Higher flow rates without effective humidification may cause drying of nasal mucosa, with associated bleeding and airway obstruction.

Methods and attachments for giving oxygen

F, French; O₂, oxygen; PEEP, positive end expiratory pressure.

Table 7.1 Comparison of oxygen delivery methods in children and infants

Methods and attachments for giving oxygen

F, French; O₂, oxygen; PEEP, positive end expiratory pressure.

Higher flow rates without effective humidification may cause drying of nasal mucosa, with associated bleeding and airway obstruction.
7.2.2 High flow nasal prongs in newborns and infants

Recently, higher flows through nasal prongs using an air-oxygen mix and humidification have been used in preterm newborns, and in infants with very severe pneumonia and severe bronchiolitis who are failing to respond to standard oxygen flow rates, or when ventilation is inadequate.\textsuperscript{70,71} “High-flow CPAP” may help to increase lung volumes, reduce atelectasis (alveolar and lung segmental collapse), and may stimulate breathing in infants with apnoea. Flow rates of up to 2 litres per kg per minute through normal nasal prongs have been used as an alternative to CPAP using a mechanical ventilator or bubble-CPAP circuit (Section 6.1.4). 2 litres per kg per minute delivers about 4-5 cmH\textsubscript{2}O of PEEP. It requires special equipment: (i) a source of gas flow (ii) an oxygen blender, and (iii) a humidifier, similar to bubble-CPAP but without the circuit (Figure 6.1).

Although PEEP can be generated by this high-flow method, it is not as simple as dialling higher flows from a standard oxygen source such as a cylinder or concentrator; this would be very dangerous. This method requires highly effective humidification to prevent drying of nasal mucosa, which can lead to bleeding and nasal obstruction. A heated humidifier is ideally used; an unheated water bubble humidifier may not provide adequate humidification at such high flows.

High-flow CPAP also requires an oxygen/air blender, so that the inspired oxygen concentration can be controlled, as it is often unnecessary and potentially dangerous to deliver very high inspired oxygen concentrations to the lungs. With high-flow CPAP there is also a risk of stomach distension and pneumothorax which needs to be carefully monitored. High-flow CPAP through nasal prongs is a promising and potentially low-cost method for providing additional respiratory support in hospitals without mechanical ventilators or standard CPAP machines, there is limited experience with this method at this stage.

If used, close monitoring of the adequacy of ventilation is necessary, as high flow oxygen can maintain Sp\textsubscript{O}\textsubscript{2} in the normal range despite dangerous hypercarbia and near respiratory failure.

7.2.3 Oxygen delivery methods in adults

The methods chosen to deliver oxygen in adults are influenced by the severity of hypoxaemia, the inspired oxygen concentration required, how long oxygen is likely to be needed and individual patient preference. Oxygen masks (Figure 7.4) require higher flows (3–6 litres/minute) than nasal prongs or catheters (2–4 litres/minute) to achieve similar inspired oxygen concentrations (Table 7.2). Higher inspired oxygen concentration can be achieved with a reservoir bag on the mask (Figure 7.5). Because of relative inefficiency, masks are not ideal in places where oxygen is scarce or in patients where oxygen therapy will be prolonged. In these circumstances, nasal prongs are the preferred method.

Many adults dislike the smell or mouth dryness from oxygen through a mask, or feel claustrophobic. Do not use masks at low flow rates because of the risk of hypercapnoea from inadequate washout of exhaled gas from the mask. For acute, severe hypoxaemia in adults, oxygen masks are appropriate as long as oxygen supplies are sufficient. For oxygen therapy lasting days or weeks, nasal prongs are much more efficient, and preferred by most patients (Figure 7.1).
Masks
Masks to administer oxygen to adults may deliver either a variable or fixed concentration of oxygen.

Masks that enable variable flow rates
The peak inspiratory flow when an adult breathes in is around 30 litres/minute, which means that when using simple masks or nasal prongs, air is always entrained around the device and dilutes the oxygen. The concentration of oxygen administered depends on the patient’s respiratory rate and depth, and the flow of oxygen. Approximate concentrations produced are shown in Table 7.2. The addition of an oxygen reservoir enables higher concentrations of oxygen to be delivered, which is useful in resuscitation.

![Figure 7.4 Oxygen delivered to an adult via a face mask](image1)

![Figure 7.5 Oxygen delivered to an adult via a face mask with oxygen reservoir](image2)
**Masks that provide fixed flow rates**

Fixed concentration devices provide a defined percentage of oxygen and are more commonly used in anaesthesia or intensive care with specific equipment. High-airflow oxygen enrichment masks (HAFOE) (e.g. the venturi mask, Figure 7.6) used in ward settings rely on the Venturi principle. Relatively high flows of oxygen passing across a narrow orifice allow entrainment of additional room air to the mask to meet the inspiratory flow of the patient. Depending on the attachment used, the masks deliver a fixed amount of oxygen – common percentages include 24%, 28%, 35% and 60%, all of which need a specific flow of oxygen to work.

Devices delivering fixed, low percentages of oxygen are designed specifically for use in patients with respiratory failure due to COPD with carbon dioxide retention (type II respiratory failure). In this unusual situation (10% of COPD patients), controlled oxygen therapy is indicated to maintain oxygen saturation at around 90% and avoid exacerbating carbon dioxide retention. The majority of patients with COPD suffer from acute hypoxia without hypercapnoea (type I respiratory failure), and in these patients the concentration of oxygen need not be limited.

![Venturi mask](image)

**Figure 7.6 Venturi mask**

**Table 7.2 Approximate levels of inspired oxygen using different devices in adults**

<table>
<thead>
<tr>
<th>Device</th>
<th>Oxygen flow (litres/minute)</th>
<th>Approximate inspired oxygen concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nasal prongs or nasal catheter</td>
<td>2–4</td>
<td>30–40</td>
</tr>
<tr>
<td>Oxygen mask</td>
<td>3–6</td>
<td>30–50</td>
</tr>
<tr>
<td>Oxygen mask with reservoir</td>
<td>3–6</td>
<td>50–75</td>
</tr>
<tr>
<td></td>
<td>5–9</td>
<td>65–90</td>
</tr>
</tbody>
</table>

**Practical aspects of oxygen therapy in adults**

Some adults do not tolerate oxygen masks well, complaining of claustrophobia, the smell and a dry throat. Often encouragement improves compliance, but as many hypoxic patients are restless or confused this can be a problem.

If nasal prongs or face masks are not available for delivering oxygen to adults, a nasal catheter can be used. These can be made from a cut-down nasogastric tube. The tube
should be inserted into the nose and then the nasopharynx, and the insertion depth should be marked with a piece of tape before the tube is taped to the upper lip and cheek. A small amount of local anaesthetic squirted into the nostril (2% lidocaine) will make insertion more comfortable. The tube must never advance into the oesophagus or trachea as severe injury (gastric rupture or pneumothorax) could result from direct exposure to the high-pressure oxygen supply. In adults the flow through a nasal catheter should not exceed 4 litres/minute. Nasal catheters produce an inspired oxygen concentration of 30–40% and depend on the patient breathing through the nose.

Face masks, nasal prongs and oxygen tubing can safely be cleaned in soap and water, soaked in dilute bleach solution and allowed to dry before reuse.

**Conserving oxygen supplies**

In many hospitals oxygen is an expensive and scarce resource. At times decisions will need to be made about whom to treat and for how long. This decision has to be made on the basis of the local situation by the clinicians involved. Where oxygen is scarce it should be remembered that even low-flow oxygen (2–3 litres/minute in adults) will relieve hypoxaemia in many patients.
8 Humidification

Some oxygen delivery methods require use of humidifiers for patient comfort. This section outlines when humidification is required, and the types of humidifiers recommended.

8.1 The need for humidification

When oxygen is used at low flow rates (<4 litres/minute) through nasal prongs, humidification is not necessary. A study of adults on long-term oxygen by nasal catheter showed there was no difference in subjective assessment of nose symptoms between humidified and non-humidified oxygen. Complaints of dry nose and dry throat occurred in more than 40% of patients, but the symptoms were relatively mild and did not increase significantly when oxygen was administered without prior humidification. Humidification of oxygen at standard flow rates by nasal prongs or catheter is not necessary.

Humidification is needed when oxygen is given via a N-P catheter, and in all patients with an endotracheal tube or a tracheostomy. A study from the Gambia showed a higher rate of nasal obstruction by mucus in children receiving oxygen by N-P catheter, and it was speculated that this might have been partially caused by dry oxygen. In general, humidification is less required if oxygen is delivered in tropical climates by a concentrator than a cylinder, as concentrators provide oxygen at room temperature whereas cylinders deliver cold oxygen.

8.2 Unheated bubble humidifiers

An unheated bubble humidifier is a simple device that adds only a little to the cost of oxygen equipment, but because it is inefficient, its role is limited. Unheated bubble humidifiers have a role when oxygen is delivered by cylinders through a nasal catheter, or if a N-P catheter is used to deliver oxygen, or if higher than standard flows are used.

Bubble humidifiers (see Figure 8.1) reduce the dryness of the oxygen supplied from a cylinder by bubbling the gas through water at room temperature. The bubble humidifier is filled with clean water (distilled water, or tap water that has been boiled and cooled). The humidifier is then firmly attached to the oxygen outlet, taking care to avoid oxygen leaks and making sure that it is bubbling.

The water level in the humidifier should be checked twice daily and topped up as necessary. Humidifier equipment must be washed and disinfected regularly to prevent bacterial colonization.

Maintenance of humidifiers is also important. The water should be changed daily. Changing the water includes washing the humidifier, water jar and catheter in a mild soapy water, rinsing with clean water and drying in air before reuse. Once a week (or whenever a patient ceases oxygen therapy), all the components of the humidifier should be soaked in a mild antisepic solution for 15 minutes, rinsed with clean water and dried in air. Allowing the humidifier to dry completely will help to discourage bacterial colonization. A spare, clean humidifier filled with clean water should always be available, so that oxygen therapy is not interrupted while the humidifier is cleaned.
The effectiveness of unheated humidifiers is modest, even at low flow rates in tropical climates.

Heated humidifiers, as illustrated in Figure 6.1, have been found to be more effective than unheated ones; however, they are expensive and require a continuous power supply. Bubble humidifiers are sufficient when giving basic oxygen therapy at standard flow rates, or at higher flow rates when a heated humidifier is not available.

8.3 Safety of humidifiers

A major safety concern with water humidifiers is bacterial contamination. In one study, prefilled disposable reservoirs were found to be pathogen free for up to 3 days, but in another study, ambulance humidifiers with multiple-use bottles yielded bacteria in 22 of 30 reservoirs. Humidifiers that used tap water were found not to be contaminated more frequently than those that used sterile water, but this may not be the case in all settings; in some hospitals tap water may be contaminated and increase the risk of hospital-acquired (nosocomial) infection.

8.4 Tracheostomy humidification

Humidification is essential for patients with an endotracheal tube or a tracheostomy. The nose and mouth provide warmth, filtering and moisture for the air we breathe. A tracheostomy tube (shown in Figure 8.2) bypasses these mechanisms. Humidification must be provided to keep secretions thin and to avoid mucous plugs. Patients who have had tracheostomies do best in an environment of 50% humidity or higher. In patients who are not ventilated, secretions can be kept thin by applying a heat moisture exchanger (HME, sometimes called a Swedish nose) to the tracheostomy tube (shown in Figure 8.2). This is a humidifying filter that fits onto the end of the tracheostomy tube; several shapes and sizes are available (all styles fit over the standard tracheostomy tube opening).

In patients with tracheostomies or an endotracheal tube who are receiving supplemental oxygen or CPAP, heated humidifiers are preferred to unheated humidifiers.
KEY MESSAGES

- Humidification is only necessary for methods of oxygen delivery that bypass the nose and is generally not necessary when oxygen is delivered through a nasal catheter or nasal prongs.
- Humidification is essential when cold oxygen is delivered from a cylinder through a nasopharyngeal catheter.
- Humidifier reservoirs should be cleaned regularly to avoid bacterial contamination.
- Humidification is essential in patients with an endotracheal tube or a tracheostomy. Endotracheal tube obstruction from inadequate humidification is the cause of many unnecessary deaths in hospitals.
Section B  Information for engineers

The most common sources of oxygen are oxygen concentrators, oxygen cylinders and oxygen pipelines. This section describes the different oxygen sources: their advantages and disadvantages, requirements, use and maintenance. It then gives information on humidifiers, which are required with some methods of oxygen delivery. Chapter 12 provides technical information about pulse oximeters.

**KEY MESSAGES**

- A wide variety of oxygen sources is available. In general, bedside oxygen concentrators will be appropriate in most small hospital settings, but need a continuous and reliable power source.

- Cylinders will be the appropriate oxygen source in hospitals and health facilities where power is not available, but they are expensive and difficult to transport.

- In larger hospitals, oxygen is often pipe-delivered to patient care areas through copper pipes from a central bank of cylinders, but leakage through pipe connections can result in much wastage of oxygen. Oxygen can also be piped from a large central concentrator.

- To get the most out of a concentrator it should be used with a flow splitter or flow meter stand that allows the provision of oxygen to multiple patients at the same time. Cost of this equipment should be included in the initial costing for each concentrator.

- A flow sensor should be used to regularly check flow at the end of the delivery tubing to ensure that patients are receiving the intended flow of oxygen.
9 Oxygen concentrators

Air is 21% oxygen, 78% nitrogen and 1% other gases. Oxygen concentrators entrain air from the environment and separate the oxygen and nitrogen by way of a pressure swing adsorption (PSA) process. An air compressor pushes the room air into a sieve bed or column filled with a regenerative molecular sieve made of zeolite, a beaded, inert, ceramic material. The sieve material allows the oxygen to pass freely through, while the nitrogen is retained under pressure. The cycle alternates between two sieve beds, allowing one bed to make oxygen while the other is depressurized, freeing the nitrogen to exit the system through the exhaust muffler. The system has four main components: an air compressor, valve(s), sieve beds and circuit board. Most concentrators supply oxygen at a concentration of 90–96%.

Oxygen concentrators were first produced in 1974. They were originally designed to provide long-term home oxygen therapy for adults with chronic lung disease in developed countries. Their use has been extended over the past 35 years; there are now many examples of concentrators successfully supplying multiple beds in busy hospitals in developing countries.

9.1 Bedside oxygen concentrators

Bedside portable oxygen concentrators typically weigh less than 25 kg (Figure 9.1). These machines provide a reliable source of oxygen for many years with minimal service and maintenance. These units are self-contained, and can supply a very economical, continuous stream of oxygen at a rate ranging from 5 to 10 litres/minute. With appropriate mechanisms to divide the flow from the concentrator, they can supply oxygen for up to multiple patients, depending on patient size and oxygen requirements. Generic specifications for bedside concentrators are listed in Annex D and should be considered when procuring equipment.

Figure 9.1 Delivery of oxygen from an oxygen concentrator to two children at once
9.1.1 Installation and maintenance of bedside oxygen concentrators

This section describes how to set up a concentrator to deliver oxygen to four patients at once from a permanent position in the ward, such as a high-dependency area (see Figure 9.2).

Oxygen concentrators are normally supplied with users and maintenance manuals that explain how the apparatus works, its limits of performance and what regular maintenance is required. Read the instructions on how to unpack and install the concentrator. Check in particular that the voltage shown on the packing list is correct for your power supply and that the plug fits the mains power socket. Very carefully read the instructions for using the concentrator and its accessories, and the information on necessary regular maintenance.

Position the concentrator close to a mains power outlet in a cool part of the ward, not in direct sunlight, with a good air supply. The room or ward should be well ventilated and there must be good air circulation around the concentrator itself: clearance on all sides should be in accordance with the manufacturer’s instructions. Keep the concentrator in the shade and at least 1.5 m away from any source of heat.

There are two ways to divide the flow from a bedside concentrator to up to four patients. Most concentrators use a flow splitter. Some manufacturers use a flow meter stand.

Fasten a back-up cylinder to the wall in a corner, with a strap or a chain,

Figure 9.2 The set-up in a ward of a concentrator that will deliver oxygen to four patients, with a back-up cylinder
Flow splitter

There are several types of flow splitters, illustrated in Figures 9.3 and 9.4.

To set up the flow splitter, connect it to the oxygen outlet on the concentrator. Carefully screw four nozzles, or a combination of nozzles and blanking plugs, into the flow-splitter ports. Make sure that all four ports have either a nozzle or a blanking plug so that oxygen does not escape through unused nozzles. It is also important that you put a blanking plug on any unused port of the flow splitter to avoid wasting expensive oxygen and to ensure that the correct flow is delivered from all nozzles.

The flow-splitter nozzles allow a fixed flow of oxygen through fixed-size orifices. Colour-coded nozzles for flows of 0.5 and 1 litre/minute are available for paediatric use. The nozzles allow accurate distribution to patients even when the oxygen distribution tubing to different patients is of different lengths. Make sure that the total flow shown on the flow controller of the concentrator does not exceed the capacity of the concentrator.
Use 1 litre/minute nozzles for oxygen therapy in young children, 2 months to 5 years old. For infants <2 months of age, use 0.5 litre/minute nozzles. If you have a 4 litres/minute concentrator and you need to give oxygen at flow rates higher than 1 litre/minute, combine the output from two nozzles using a Y-connector; for example, combine a 0.5 and a 1 litre/minute nozzle to give 1.5 litre/minute. Some concentrators come with 2 litres/minute nozzles.

Connect four lengths of oxygen distribution tubing (5 mm internal, 8 mm external diameter) to the nozzles and fix them with simple cable clips to the wall at about eye level (see Figure 9.5). Be careful to avoid damaging or kinking the tube. Alternatively the tubing can be encased in conduit, which gives more protection and avoids the use of cable clips. Each of the four tubes can be up to 15 m long and will end beside a bed or cot.

Figure 9.5  Oxygen distribution tubing attached to a flow splitter and fixed to the wall

Attach a flow indicator to the end of the oxygen distribution tubing or to the outlet of the bubble humidifier. This device confirms that the oxygen flowing to the patient exceeds 0.35 litre/minute by showing a green band or a rotating vane. A red band appears or the vane stops rotating if the flow falls below this level. Connect the non-crush oxygen delivery tubing of the nasal prongs or a 2-m length of non-crush oxygen delivery tubing to the flow indicator. Finally, connect the catheter to this non-crush plastic delivery tubing if you use nasal or N-P catheters for the administration of oxygen.
Flow meter stand

Some concentrator manufacturers have a flow meter stand as an alternative to a flow splitter. This has the advantage of being more familiar to clinical staff who are used to using flow meters on cylinders. The flow is simply dialled up for each patient, as long as the aggregate flow does not exceed the flow from the concentrator. Figure 9.6 shows a flow stand that can provide oxygen to up to five patients at once.

![Flow meter stand](image)

Figure 9.6  A concentrator can deliver oxygen to one or more low-flow patients at a time if it is equipped with a flow meter stand

The equipment needed to administer oxygen to up to five patients from an oxygen concentrator is summarized in Table 9.1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen concentrator</td>
<td>1</td>
</tr>
<tr>
<td>Flow splitter or flow meter device</td>
<td>1</td>
</tr>
<tr>
<td>Nozzles of 0.5 and 1 litre/minute if using flow splitter</td>
<td>4 each</td>
</tr>
<tr>
<td>Blanking plugs if using flow splitter</td>
<td>3</td>
</tr>
<tr>
<td>Plastic tubing 5 mm internal diameter</td>
<td>Up to 15 m x 4</td>
</tr>
<tr>
<td>Cable clips</td>
<td>100</td>
</tr>
<tr>
<td>Flow indicators</td>
<td>4</td>
</tr>
<tr>
<td>Non-crush plastic oxygen delivery tubing</td>
<td>8 m</td>
</tr>
<tr>
<td>Prongs (or catheters)</td>
<td>4</td>
</tr>
<tr>
<td>Back-up cylinder with regulator and flow controller</td>
<td>1</td>
</tr>
</tbody>
</table>

With the system for the delivery of oxygen in place, connect the power supply cable to the concentrator, and plug it into the main power socket. Do not use an extension cable. After the concentrator is switched on a continuous alarm will sound for up to one minute; this is normal. The concentrator should be allowed to run for 5 minutes before use at the desired flow, after which time the oxygen concentration will be up to the specified optimal performance of 87% O₂. If there is no power supply, or other problems arise, an alarm will sound; refer to the user manual in these cases.
Once the concentrator is running, adjust the flow rate to the required value in the litres/minute flow range of the concentrator (i.e. 1–4 litres/minute or up to 8 litres/minute in larger concentrators, whatever the capacity) by turning the control knob of the flow meter anticlockwise. Read the flow-rate markings at the centre of the ball. If the flow meter is equipped with backlines, the proper viewing angle is achieved when the two lines appear as one.

**Testing after installation**

After the installation of all the delivery tubing, the concentrator should be tested as described below.

**Testing flow**

Test the flow by (a) submerging the oxygen catheter in water (Figure 9.7) or (b) by using an in-line flow indicator (Figure 9.8).

(a) **Flow testing under water.**

This is a simple test. Attach nasal prongs to each tubing outlet and check the flow from the prongs by immersing under water. Observe the difference in bubbling rate when the flow is adjusted between 0.5 and 1 litre/minute (see Figure 9.7).

(b) **Flow testing using an in-line flow indicator.**

Adjust the flow meter on the concentrator to 4 litres/minute and check that the flow from each delivery tube is 1 litre/minute. Then check at a flow of 2 litres/minute for four equal flows of 0.5 litre/minute. For concentrators with a higher flow (e.g. 8 litres/minute), check for equal flows from each port at maximal flow.

![Figure 9.7 Simple flow testing for an oxygen concentrator](image-url)
Testing concentration

An oxygen concentration status indicator (OCSI) should be fitted to models meeting ISO 8359 specifications. The indicator shows a green light to indicate normal operation and a concentration of oxygen greater than 85% by volume. A yellow light indicates that the oxygen concentration is between 70% and 85% by volume. A red light indicates that the oxygen concentration is below 70% by volume; a continuous alarm will sound in this case (see Figure 9.9). If this happens, refer to the user and maintenance manuals. The most usual causes of yellow and red lights and the appropriate remedies are listed in Table 9.2.

Note: The lights indicate adequate or below normal oxygen concentration; a flow meter is shown to the left.

For more precise measurement of oxygen concentration, an oxygen analyser can be used. However, these do not come with the concentrator and cost about US$ 150–400; they are, therefore, mostly used by a biomedical engineer in the regional health system.
Table 9.2 Causes of alert lights on the oxygen concentrator status indicator and their remedies

<table>
<thead>
<tr>
<th>Cause</th>
<th>Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dirty filters</td>
<td>Wash or change filters</td>
</tr>
<tr>
<td>Low voltage</td>
<td>Use a voltage regulator</td>
</tr>
<tr>
<td>Flow exceeding maximum capacity (e.g. 4 or 8 litres/minute depending on concentrator size)</td>
<td>Reduce flow</td>
</tr>
<tr>
<td>Hot and humid weather</td>
<td>Reduce flow</td>
</tr>
</tbody>
</table>

9.2 Other types of concentrators

9.2.1 Very light-weight portable oxygen concentrators

There is now a class of smaller portable oxygen concentrators, known as POCs. These miniaturized oxygen concentrators have been available since 2002. Because of their small size, they enhance ambulation and travel for oxygen-dependent patients. POCs can weigh less than 2 kg, and operate on multiple power sources: internal battery, external battery, AC or DC power. When the unit operates on mains power, its battery is recharged. These devices utilize a built-in oxygen conserving device, which allows a measured amount of oxygen to flow only during the beginning of the patient’s inhalation phase. Oxygen conserving devices eliminate oxygen waste, so the POC is smaller and lighter and runs for a longer time on battery. These concentrators are much more expensive than bedside portable oxygen concentrators and are not suitable for multiple patients, so they are unsuitable for use in hospitals in developing countries.

9.2.2 Oxygen generators

Larger oxygen concentrators are often referred to as oxygen generators, and work on the same principle as bedside concentrators. These systems provide higher capacities in both oxygen output and oxygen outlet pressure (up to 3500 kPa). They can be self-contained and supply oxygen to anaesthesia machines, ventilators, and other medical devices and accessories (Figure 9.10), or can be custom designed to supply all or a portion of the oxygen needs of the hospital facility when connected to the medical oxygen or gas pipeline.

Figure 9.10 An oxygen generator can supply anaesthetic machines
Hospital administrators, engineers and equipment suppliers should review the requirements of the facility to properly select or construct an economical oxygen system. Where an oxygen generator is selected as a source, the size and the design of the oxygen system should meet the guidelines of ISO standard 10083 (see Annex G, “Technical resources”).

The power consumption for the system depends on the size of system. Typically, the power consumption is approximately 1 kilowatt hour to produce 1000 litres of oxygen.

**Refilling cylinders from oxygen generators**

Cylinders can be refilled from oxygen generators to 15 000 kPA with additional oxygen compressors. A secondary process can concentrate the oxygen up to 99%. These systems can fill from 2 to 200 cylinders per day (see Figure 10.5).

Hospital administrators, engineers and oxygen concentrator manufacturers need to review the clinical requirements of a facility to properly select or construct an economical oxygen system to meet their requirements (Table 9.3). Oxygen generators are designed for continuous operation and can produce oxygen 24 hours a day, 7 days a week for up to 40 000 hours (approximately 5 years).

**9.2.3 Future trends in oxygen concentrator technology**

There continue to be improvements in the design and manufacture of oxygen concentrators, resulting in smaller, lighter, quieter, more power-efficient, and less expensive models. New models of oxygen concentrators appear every year. However, within a hospital or health service, standardizing on one model helps ensure continuity of spare parts, maintenance and training.

As liquid oxygen and cylinders are expensive and difficult to transport, there is now an increasing move toward the use of oxygen concentrators. Concentrators can produce an unlimited quantity of oxygen. This makes them suitable for any application, from a small clinic to a 1000-bed teaching hospital. Oxygen concentrators have proven to be the most economical way to provide oxygen therapy throughout the world.

A challenge for oxygen concentrators is in the use of alternative, renewable or hybrid sources of power, to solve the problem of running concentrators and other electricity-dependent medical equipment in health facilities with unreliable or no mains power. Another challenge that is likely to be met in the near future is to have concentrators that require minimal maintenance for an extended period of time, such as 5 years.
Table 9.3  Key technical points and specifications for oxygen concentrators suited for use in a district hospital ward

- The concentrator should achieve >85% oxygen concentration at a flow rate of up to 10 litres/minute.
- The concentrator should operate at power and frequency that is suitable for the local power supply; this differs between countries.
- For energy efficiency the power requirements should not exceed 350 W for units providing 5 litres/minute, 410 W for 8 litres/minute units, and 600 W for 10 litres/minute units.
- The concentrator should have a minimum efficiency of 850 litres/kilowatt hour for units providing 5 litres/minute, 1150 litres/kilowatt hour for 8 litres/minute units and 1000 litres/kilowatt hour for 10 litres/minute units.
- The concentrator should have one or two outlets with individual flow controls and flow indicators.
- Outlet pressure should be no less than 55 kPa for units providing 5 litres/minute and 138 kPa for 8 and 10 litres/minute units.
- Weight should not exceed 25 kg.
- An hour meter should record total hours of unit operation.
- Maximum operating altitude should be not less than 2000 m, with not less than 85% oxygen concentration at maximum flow.
- Maximum operating temperature should be not less than 40 °C.
- Maximum operating humidity should be not less than 95% relative humidity.
- A list of all spare or replacement parts and their costs for 40 000 hours of operation (e.g. compressor, sieve beds and valve spares kits) should be provided.
- The concentrator should comply with ISO 8359:199675 and IEC 60601-177 and carry a CE marking.
- A user manual intended for hospital use and a service manual with a troubleshooting guide should be provided.
- There should be a 60-month parts warranty.
- The unit should include a 4-way flow splitter, together with all nozzles and blanking plugs, which can deliver flows of 0.5, 1.0 and 2.0 litres/minute (see Figure 9.4); OR a flow meter stand (Figure 9.6). Each flow meter should be continuously adjustable from 0.5 to 2 litres/minute.

9.3 Power supply

Oxygen concentrators are available in a variety of voltages and frequencies to match the power supplies of the countries in which they are to be operated. They require a continuous AC power source, most commonly a reliable mains electricity source and a back-up generator in case of a power failure. Any power source can be used, including generators and solar power. The economics of these systems, including sizing, costing and payment can be discussed with the manufacturer of the oxygen concentrator and local suppliers of alternative power sources. Solar power systems will need to include solar panels, batteries, a charge controller and an inverter. They are high in capital costs but cheap to run and can be cost effective if properly designed and maintained.
Absence of a reliable power supply is a common reason for failure of oxygen concentrators. In the Solomon Islands, limitations in power meant that effective use of oxygen concentrators was only possible in hospitals in the major centres. In Sierra Leone, where concentrators were the only oxygen source, supply was frequently interrupted by lack of mains power and by the high cost of fuel for generators. This is a major limiting factor in some countries.

In one remote rural hospital in the Gambia, concentrators were run using solar power. This was a high-cost installation, and 6 hours of sunlight per day was necessary to power the concentrator. The authors calculated that the system became cost effective if a hospital needed more than six treatment days of oxygen per month.

A universal power supply (UPS) can be useful in settings where power is unreliable. However, it is important to note that a UPS only provides power for a few minutes after the mains power goes off. It allows time to switch to an alternative power source, such as a generator. A UPS can also protect concentrators and oximeters from power surges. However, UPS devices are expensive.

### 9.4 Safety procedures

Refer to the manufacturer’s operating and service manuals for details on operating, maintaining and servicing oxygen concentrators. Below are general guidelines regarding the use and service of oxygen concentrators.

Oxygen concentrators manufacture high-concentration oxygen, which can promote fire. Do not allow smoking or open flames within 2 m of the device or any of the oxygen-carrying accessories. Do not use oil, grease or petroleum-based products on or near the unit.

Position the unit away from curtains or drapes, hot air registers, heaters and fireplaces. Be certain to place the unit so that all sides are at least 30 cm away from a wall or other obstruction. Do not place the unit in a confined area.

When not in use, do not leave a nasal catheter or prongs in contact with bed sheets or blankets; this is an infection control hazard and also a fire hazard if the concentrator is turned on, as the oxygen will make the bedding material flammable. Set the concentrator power switch to “off” when it is not in use. Firebreak connectors are recommended which will stop the oxygen flow in the event of fire.

Face masks, nasal prongs and oxygen tubing can safely be cleaned in soap and water, soaked in dilute bleach solution and allowed to dry before reuse.

### 9.5 Maintenance

#### 9.5.1 Weekly maintenance by clinical staff

Portable oxygen concentrators have an external, coarse, cabinet air filter over the air inlet, which is often at the back of freestanding or portable concentrators (Figure 9.11). As this filter becomes dirty, less air can pass through it. If the filter is left to occlude, oxygen production can be reduced and the unit may eventually shut down as a result of elevated internal temperatures. This filter must be washed at least once a week in detergent, rinsed with clean water, dried and replaced. A spare filter should be inserted if the concentrator continues to run during cleaning.
The exterior of the oxygen concentrator should be cleaned with a mild disinfecting cleaning agent or a diluted solution of bleach (5.25% sodium hypochlorite). A solution in the range of 1:100 to 1:10 of bleach to water can be used effectively, depending on the amount of organic material present. Allow the solution to remain on the surface for 10 minutes and then rinse off and dry.

![Image of oxygen concentrator with a filter being removed](image)

**Figure 9.11** The external, large-pore filter on a concentrator needs to be removed and cleaned each week

### 9.5.2 Maintenance by the hospital engineer or service technician

Oxygen concentrators have an alarm to signal power failures. Where a battery is used for alarm activation, it should be tested and maintained as necessary. To test, disconnect the oxygen concentrator from its power source, and turn the power switch to the “on” position. For those models using a capacitor to power the alarm, the unit may need to be operated for a period of time to provide a charge to the capacitor.

The oxygen concentrator should be tested at regular intervals to confirm that the oxygen concentration is within specifications. If humidification is used, first remove the humidifier from the line, and connect a calibrated oxygen analyser to the outlet. Turn the flow meter to the maximum capacity of the concentrator and allow it to operate for a period of at least 5 minutes for the unit to stabilize before taking readings. If the unit’s oxygen monitor is indicating a low oxygen concentration, an independent test like this is valuable to determine if the monitor has failed or the oxygen concentrator is in need of service. If the unit is performing below the manufacturer’s specifications, service is required.

All oxygen concentrators will have an internal fine particle filter. These should be inspected and replaced at intervals according to the manufacturer’s instructions. Some internal filters, when dirty, can cause the unit to perform below specifications because of diminished airflow to the compressor and a resultant decrease in oxygen production.
Oxygen concentrators commonly have four major components. An understanding of each of these components and their function greatly enhances the technician’s ability to properly maintain, diagnose and repair a concentrator.

The compressor

The compressor is the “pump” within the oxygen concentrator that pushes room air into the sieve beds and allows oxygen to flow out. The two different aspects of the compressor that can cause concern are the output and the noise. The output refers to how much compressed air the compressor can produce. This depends on the model of the compressor, its stroke size, bore size and cup seal condition. The cup seals form the seal between the piston and the cylinder wall. As the cup seals wear, the compressor’s output gradually decreases, and there is a slight increase in sound caused by the air leaking around the seal. This reduced output means less air is sent into the sieve beds, and less oxygen is produced. As this drop in oxygen production occurs slowly, regular preventive maintenance on the compressor is not required. Only when there is a measurable decrease in the unit’s oxygen production or the operating system pressure will the compressor require rebuilding or replacement.

The condition of the compressor’s bearings also determines its sound level. There are four bearings in the compressor that allow the inner components to rotate. As the bearings become worn, the noise level increases noticeably, and service is required. Refer to the manufacturer’s service manual for instructions for rebuilding or replacing the compressor.

Valves

The valves, or valving system, control the PSA process within the oxygen concentrator. They control the pathway of the compressed air that feeds and pressurizes one sieve bed while the other sieve bed is allowed to depressurize and purge the nitrogen through the exhaust muffler. Many types of valves (4-way, 3-way, 2-way, rotary, spoon and sleeve, diaphragm, and poppet) are found within different models of oxygen concentrators. Some valves can be opened and serviced, but others are sealed. The type of valve in the concentrator will directly influence the need for filtration. Highly sensitive valves with extremely small tolerances are very susceptible to sticking due to particulates, dust, dirt, smoke and surface corrosion caused by humidity. They therefore require a high degree of filtration. Two-way poppet valves are designed, and have demonstrated proven performance, to operate reliably in very humid climates with elevated temperatures. It is highly recommended that the oxygen concentrator selected has a valving system proven to be suitable to the conditions where the unit is to be operated.

Sieve beds

The sieve beds hold the molecular sieve material where gas separation takes place. The material is regenerative and stores nitrogen under pressure while allowing oxygen and argon to pass through freely. As well as nitrogen, the sieve material has an attraction for water molecules. Water in the feed air is contained within a water zone of the sieve bed, and on depressurization is released along with the nitrogen as part of the purge gas. A controlled amount of sieve is intentionally exposed and allowed to “contaminate” with water molecules forming the water zone. In a well-designed and properly operating PSA system, the water zone remains constant, even when exposed to high humidity and ambient temperatures.

Sieve material within the sieve bed can become contaminated in a number of ways. A leak in the system, especially on the product side, allows water molecules in room air to come in contact with and contaminate the sieve material. The sieve material needs to be
tightly packed and contained within the sieve bed. Most manufacturers use a spring-loaded piston design, which keeps pressure on the sieve to prevent it from shifting. If the material moves or migrates, the contaminated sieve in the water zone will move throughout the bed.

If the alternating PSA cycle of feeding and purging the beds is interrupted, the beds can become contaminated. A failure to cycle could be caused by a defective valve or printed circuit board (PCB), which controls the valves. This could result in one bed being fed room air continuously. This introduces more water molecules than the water zone can contain, expanding the water zone into the active part of the bed. Care should be taken to thoroughly leak-test a unit and repair any leaks that can result in sieve bed failure. To detect leaks, spray or apply a solution of soapy water to all fittings and connections, from the air compressor to the oxygen outlet.

Argon, along with the oxygen, passes freely through the sieve material and is allowed to concentrate, so the maximum oxygen concentration obtainable will be 95.5%, with the remainder being argon and a small amount of nitrogen.

**Printed circuit board**

The PCB is the electronic control for operating the valve(s) and alarm system. If the PCB fails, the unit may not cycle properly or may not operate at all. Some systems have a lighting and diagnostic system located on the PCB to aid in troubleshooting.

Table 9.4 gives a guide to troubleshooting some of the more common problems found with oxygen concentrators. Consult the service manual for additional troubleshooting suggestions.
Table 9.4  Troubleshooting guide for the hospital engineer or service technician

<table>
<thead>
<tr>
<th>Problem</th>
<th>Probable cause(s) and solution(s)</th>
</tr>
</thead>
</table>
| The oxygen concentrator does not turn on    | No power from the mains  
Inspect and check power cord, electrical connections, circuit breaker (if equipped), internal fuse (if equipped; sometimes located on the PCB), on/off switch, PCB |
| The oxygen concentrator operates, but the compressor shuts down intermittently | Check cabinet filter, cabinet fan, capacitor for the compressor, cabinet thermal switch (if equipped), valve(s), PCB  
Compressor may have a faulty internal switch |
| The oxygen concentrator’s compressor does not turn on | Inspect and check electrical connections to the compressor, capacitor, PCB, valve(s), compressor |
| The oxygen concentration is within specifications, but flow fluctuates | Pressure regulator needs to be adjusted, repaired, or replaced |
| The oxygen concentration is within specifications, but the oxygen monitor indicates low concentration | Tubing to oxygen monitor is kinked, faulty oxygen monitor |
| The oxygen concentrator runs, but oxygen concentration is low | For these situations it is very useful to test the system’s operating cycle pressures for determining which component is in need of repair or replacement; refer to the service manual for instructions on how to test system pressure  
Low system pressure can indicate a restriction to the intake of the compressor, a leak, a worn compressor, valve, PCB  
High system pressure can indicate contaminated sieve beds, restriction in the exhaust muffler, valve, PCB |

PCB, printed circuit board.

Maintain regular contact with the manufacturer’s technical support department. This can be established via email, and will allow you to receive updates on equipment and service manuals. Technical support offers troubleshooting assistance and recommends spare parts inventories, based on historical reliability data. Many manufacturers will provide technical training, either at their facility or on-site.

To properly support the oxygen concentrators in your facility, you will need to maintain an inventory of spare parts, which should include the major components, components that wear and most, if not all, electrical components. Items to consider include compressors, compressor mounts, sieve beds, valves, PCBs, on/off power switches, power cords, hour meters, circuit breakers, fuses, cabinet fans and tubing, fittings and filters. This inventory of parts should be adjusted according to the number of concentrators being supported. This is where the manufacturer can be of great assistance in recommending quantities and parts commonly used. These parts should be included in the initial purchase contract. Concentrators will not run without regular maintenance and replacement of parts.
10 Oxygen cylinders, pipelines and humidifiers

Where oxygen concentrators are not practical, oxygen can be supplied from cylinders. In some larger facilities, oxygen is distributed to patient care areas from a central source via pipelines. Humidifiers prevent cold, dry oxygen from drying respiratory secretions when oxygen is delivered directly into the nasopharynx (using a N-P catheter or high flow-through nasal prongs) or lower in the respiratory tract (such as through a tracheostomy or endotracheal tube).

10.1 Oxygen cylinders

Oxygen cylinders come in several sizes, the commonly used sizes are listed in Table 10.1. Because of their size and weight cylinders are difficult to transport, and require care during transport to avoid damage to vehicles and fire risk. Cylinder oxygen is relatively expensive, but where oxygen concentrators are impractical, for example where the power supplies are unreliable, they can be used as an alternative or back-up to these.

<table>
<thead>
<tr>
<th>Size</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (litres)</td>
<td>400</td>
<td>1500</td>
<td>4000</td>
<td>7000</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>500</td>
<td>650</td>
<td>900</td>
<td>1500</td>
</tr>
<tr>
<td>Diameter</td>
<td>110</td>
<td>180</td>
<td>204</td>
<td>230</td>
</tr>
<tr>
<td>Weight when full (kg)</td>
<td>3.4</td>
<td>13.6</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 10.1 The capacity and dimensions of oxygen cylinders in common use in health facilities

Oxygen for cylinders is produced by compressing and cooling air until it liquefies, and then distilling the liquid to separate the pure oxygen. The oxygen (and other gases, particularly nitrogen) is then collected and stored under pressure in cylinders. Because of the very low temperatures required (below –180 °C), this process is restricted to large manufacturing plants. It is an expensive, energy-consuming process.

Industrial oxygen is often much cheaper than medical oxygen and may be easier to obtain. As the principle of manufacture is identical for both forms, chemical impurities are unlikely. See section 12.3.1 for more details on when oxygen cylinders are used.
Oxygen cylinders, which run off very high pressure, require a regulator, also known as a reducing valve, to reduce this pressure to a constant lower working pressure, and to allow the flow of gas to be controlled.

There are a number of different cylinder connectors; the regulator must match the cylinder connector. The most commonly found connectors are the pin-index and the bull-nose (Figures 10.2 and 10.3), but others exist in different parts of the world: handwheel, air liquide and American olive. Before ordering a regulator, the user must check which type of connector is needed.
Regulators should include a high-pressure gauge that indicates the amount of oxygen remaining in the cylinder. Full cylinders usually contain oxygen at a pressure of about 13 400 kPa (132 atmospheres or bars, or 2000 psi). When the pressure falls below 800 kPa (8 atmospheres or bars, or 120 psi), the cylinder is nearly empty.
A flow meter or other flow control device must be attached downstream from the regulator to allow the flow of oxygen to the patient to be precisely set (see Figures 10.1 and 10.4). There are two sorts of flow control devices:

- **Variable-orifice flow meters**, in which the flow is controlled by a knob that adjusts a needle valve. The flow is usually indicated by a ball in a tube. For paediatric use it is desirable to have a flow meter with a range of 0–2 or 0–4 litres/minute, rather than the 0–10 or 0–15 litres/minute flow meters commonly used for adults.

- **Fixed-orifice flow controllers**, in which the flow is controlled by a series of fixed-size openings, using a control knob. Flows of 0.5, 1.0, 1.5, 2.0, 4.0 and 5.0 litres/minute are usually available. Fixed-orifice flow controllers are often sold already combined with a regulator in a single unit.

Variable-orifice flow meters are most widely used. Health workers are more likely to be familiar with this sort of flow control device. They allow any flow within the range and limits of accuracy of the instrument to be set. Flow meters for adults (from 0–15 litres/minute) are readily available. Low-flow paediatric versions are often more expensive and sometimes difficult to obtain. It is possible to use adult (higher) flow meters in children, but the precision of flow regulation is less accurate.

Fixed-orifice flow controllers are accurate at the flows for which they are designed. They are more robust than variable-orifice flow meters. For paediatric use they must be capable of delivering flows of 0.5, 1.0 and 2.0 litres/minute. Usually they offer other flows, and a range up to 5 litres/minute is desirable. They cannot give flows intermediate between their fixed settings, but intermediate flows are prescribed rarely, and such small adjustments of flow are always limited by the accuracy of the instrument and the skill of the user.

Either type of flow control device is adequate. Variable-orifice flow meters are more widely available, but new purchasers may choose fixed-orifice flow controllers because of their robustness, compactness and possible cost advantage. A regulator and a flow control device in a single unit is less likely to get lost or damaged.

Oxygen cylinders can be adapted to give oxygen to more than one patient at the same time. A system using a 4-way adaptor to deliver oxygen from a single cylinder to three patients is illustrated in Figure 10.4.

![Figure 10.4](image-url)

**Figure 10.4** Cylinder and regulator, 4-way adaptor, flow meters and bubble humidifiers to treat three patients at once
When using oxygen cylinders it is important to tighten all connections between the cylinder and the regulator and between the regulator and the flow meter, so oxygen does not leak. Before the cylinder is used to supply oxygen to a patient, the regulator should be opened and the amount of oxygen remaining checked. If the needle of the gauge on the regulator is in the red zone the cylinder is nearly empty; a full replacement cylinder should be used. A cylinder which is nearly empty should never be used overnight, as the oxygen supply may run out.

### 10.1.2 Refilling oxygen cylinders

In some areas it may be economical to refill oxygen cylinders on-site (see Figure 10.5). Several concentrator manufacturers have recently begun offering small, portable, self-contained oxygen cylinder refilling plants capable of refilling 55 B-size, 17 E-size, 4 M-size or 2 H-size cylinders of oxygen per day. These use standard oxygen concentrators in conjunction with small oxygen compressors to refill oxygen cylinders to 15 000 kPa pressure. Although experience is limited, such units may prove to be economical to use in small, remote hospitals. For larger hospitals, custom-built oxygen cylinder filling plants are available in any size.

![Diagram of an oxygen concentrator with a compressor](image)

**Figure 10.5** An oxygen concentrator with a compressor can be used to fill cylinders
10.2 Oxygen pipelines

In many larger hospitals oxygen is distributed through a system of copper pipes from a central source of oxygen, usually located outside the building. The sources may be liquid oxygen, high-pressure gaseous oxygen cylinders, a large oxygen concentrator or a combination of these. A detailed specification for pipelines to carry oxygen and other medical gases is given in ISO 7396-1:2008. Pipelines typically deliver gas at pressures of about 400 kPa (4 atmospheres or bar). This enables equipment such as anaesthetic machines and ventilators, which require a high pressure, to be powered by the gas. A pipeline system has many safety advantages: it reduces the risk of fire and avoids handling of heavy cylinders and their transportation between hospital wards. However, the high cost of installation of centralized oxygen sources with copper pipelines, as well as the maintenance needed to prevent leaks from copper pipes and terminal units, make these systems of oxygen delivery unsuitable for district-level hospitals in developing countries.

10.3 Anaesthesia systems and oxygen supplies

Different designs of anaesthesia systems require different amounts of oxygen to operate. Drawover anaesthesia apparatus is economical, delivering an inspired oxygen concentration of 35–40% at around 1 litre/minute of oxygen flow, and an inspired oxygen concentration of around 80% at 5 litres/minute flow. Small oxygen concentrators, which can deliver 5–8 litres/minute, can be used with drawover anaesthesia apparatus.

More complex continuous-flow anaesthesia machines (plenum machines) are in widespread use, but they rely on a supply of compressed gas, either from cylinders or piped oxygen. They use several times the gas flow used by drawover apparatus. Continuous flow anaesthesia machines require less gas flow if used in conjunction with closed or semi-closed anaesthesia circuits. These consist of an in-line carbon dioxide absorber canister, breathing bag, inspiratory and expiratory valves, fresh gas supply and a pressure-relief valve (for more information see http://www.frca.co.uk/article.aspx?articleid=100143).

Care should be taken to choose appropriate anaesthetic equipment for the work required and the resources and oxygen supplies available.

10.4 Humidifiers

The use of a humidifier is not necessary when oxygen is delivered at standard flow rates (up to 1 litre/minute in neonates and up to 2 litres/minute in infants) into the nose by a nasal catheter or prongs, but humidification is recommended if higher flow oxygen is used. Humidification is essential when oxygen is delivered through a N-P catheter.

Humidifiers prevent cold, dry oxygen from drying respiratory secretions, which can cause blockage of the nose or throat. There are several types, but most commonly used in simple oxygen systems is a bubble humidifier, in which the oxygen is bubbled through water. The efficacy of these humidifiers is uncertain.

Some bubble humidifiers have a high-pressure alarm in the lid, in the form of a whistle, that sounds if the tubing blocks or kinks between the humidifier and the patient. If the whistle sounds, inspect the tubing for blockage, and if there is no obvious block in the tubing, remove the oxygen delivery catheter and clean it.
Humidifiers contain many connections and seals and may be a source of leaks in an oxygen system. Humidifiers are also subject to bacterial contamination, with the risk of consequent patient infection, and require daily attention to prevent this. If you only give oxygen using nasal catheters or prongs, humidifiers are not necessary; this is a great advantage of these routes of oxygen delivery.

For more information on humidifiers and their day-to-day maintenance, see Chapter 8.
11 Pulse oximetry: technical aspects and specifications

This chapter describes the biomedical engineering aspects of pulse oximetry, and specifications for oximeters used in small hospitals. The clinical application of pulse oximetry and the range of sensor probes that are available are described in Chapter 5.

Pulse oximetry is the most accurate non-invasive method of detecting and monitoring hypoxaemia. Pulse oximetry can be a highly cost-effective intervention in hospitals that care for large numbers of children with acute respiratory disease.36

The symbol for oxygen saturation as measured by a pulse oximeter is SpO₂, which stands for haemoglobin oxygen pulsed saturation.

11.1 How does a pulse oximeter work?

Haemoglobin carries oxygen in the blood. The principle of pulse oximetry is based on the differing red and infrared light absorption characteristics of oxygenated and deoxygenated haemoglobin. Oximetry uses spectrophotometry, which measures the absorbance of red and infrared light after it has passed through the body tissues, to measure the percentage of haemoglobin that is fully saturated with oxygen (SpO₂). The pulse oximeter consists of a computerized unit and a sensor probe, which is attached to the patient’s finger, toe or ear lobe. This sensor probe emits two different wavelengths of light, commonly 650–660 nm (red light) and 910–940 nm (infrared light).35;80 Oxygenated haemoglobin absorbs more infrared light and allows more red light to pass through, and the reverse is true for deoxygenated haemoglobin. The ratio of absorbed red to infrared light indicates the degree of oxygenation of the blood.

With each arterial pulsation, the absorbance characteristics of tissues change with the inflowing blood. Blood flow to tissues can be represented as a plethysmographic wave. Arterial pulsations appear as peaks in this wave and these peaks can be considered to represent the absorbance of light by venous blood and other tissues; this is the baseline absorbance. Pulse oximeters subtract the baseline signal from the signal at the peak of the plethysmographic wave and the difference represents the signal due to inflowing arterial blood. A microprocessor inside the oximeter compares the absorption of red and infrared light at the peak (arterial pulse) and the trough (baseline). The pulse oximeter measures “functional” saturation, which is the ratio of oxyhaemoglobin to the sum of all the functional haemoglobins.35

The oximeter displays the SpO₂, together with an audible signal for each pulse beat, a pulse rate and, in most models, a graphical display of the blood flow past the probe (the plethysmographic or pulse wave) (see Figures 5.7, 5.8 and 5.9).
11.2 Safety features of pulse oximeters

An adjustable in-built low-saturation alarm is included in most oximeter models to alert health workers when a patient is hypoxaemic. This can be set at any threshold, but it is often set at 90% or 85% so that dangerously low saturation levels can be easily identified. A high-saturation alarm is useful if there is a need to limit the oxygen saturation achieved by administered oxygen, such as when managing very premature neonates (see section 6.1.3).

A low-battery alarm is essential to alert health workers when the machine needs to be plugged into a power supply (AC mains). It is very important that the oximeter is connected to mains power whenever it is not being used around the ward. If the internal battery discharges, it will only work if plugged into the mains and its utility as a portable monitoring tool will be limited.

The key technical points to consider when choosing pulse oximeters are listed in the box below.

<table>
<thead>
<tr>
<th>Key technical points and specifications of pulse oximeters suitable for district hospitals</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Know the voltage range and the frequency of the mains power source where the pulse oximeter will be used. Models are available for 240 V/50 Hz; 240 V/60 Hz; or 120 V/60 Hz.</td>
</tr>
<tr>
<td>• There are many types of oximeters, including hand-held and table-top devices. Larger models cost about US$ 1000 and smaller versions cost US$ 100 or less. Hand-held models may be more susceptible to theft, and the internal battery may not be rechargeable from mains power.</td>
</tr>
<tr>
<td>• Weight, operating temperature and operating humidity should all be considered.</td>
</tr>
<tr>
<td>• A hard, robust casing is necessary to prevent damage.</td>
</tr>
<tr>
<td>• Accuracy range is usually ±2% at an SpO₂ between 70% and 100%.</td>
</tr>
<tr>
<td>• The range of pulse rate measurements should cover 0–250 beats/minute.</td>
</tr>
<tr>
<td>• It is important that the internal battery can be recharged from mains power.</td>
</tr>
<tr>
<td>• The oximeter should be able to run on the internal battery for at least 8 hours.</td>
</tr>
<tr>
<td>• A plethysmographic display (either a waveform or a liquid crystal bar graph) is useful for determining the accuracy of measurement.</td>
</tr>
<tr>
<td>• The pulse oximeter should comply with ISO 9919:2005, IEC 60601–1, and carry a CE marking.</td>
</tr>
<tr>
<td>• The limiting component in pulse oximetry is the sensor probe. With appropriate care, good quality probes can last 12 months. Suppliers should be selected on the basis of a guarantee of 12 months product use. Oximeters should be bought with a commitment to supply sensor probes for 5 years to ensure machines do not fall into disuse because the probe malfunctions.</td>
</tr>
<tr>
<td>• Sensor probes with soft casings are available for use on neonates, infants and older children.</td>
</tr>
</tbody>
</table>
Section C  Information for hospital administrators and managers

KEY MESSAGES

- A high-dependency area within a hospital ward, where oxygen can be given and near where nurses are most available, helps group together the sickest patients in the one place.

- A multi-disciplinary oxygen team, including a biomedical engineer, a senior clinician (such as a paediatrician, physician or child-health nurse) and an administrator is desirable to support the organizational, technical and training aspects of oxygen systems. This team provides an important national resource for information and uniform planning.

- Technical expertise in procurement, commissioning and installation is important. There is a wide variety of quality in the machines that are on the world market.

- Uniformity of equipment is important where possible, to ensure compatibility of spare parts and to limit confusion among health workers and engineers. Spare parts (including filters and sieve beds) should be provided for at least 5 years of operation (or 40 000 running hours).

- To get the most out of each concentrator, flow splitters or a flow meter stand that allow oxygen to be provided to several patients at the same time should be used; costing for flow splitters or a flow meter stand should be included in the initial costing of each concentrator.

- Building capacity within hospitals and the health department in maintenance and repair is vital; relying on local agents to service equipment may lead to long delays and high costs. Preventive maintenance is essential, and the failure to provide it results in costly repairs and downtime of equipment.

- Simple guidelines should be provided on the clinical use of oxygen and on the regular preventive maintenance of oxygen concentrators.

- Training should be provided for nurses, doctors and hospital engineers on-site, when equipment is being installed in hospitals. Such training takes 1–2 days, and needs to be reinforced by in-service training during regular visits by the oxygen team. Repeated in-service training is especially important in countries with high staff turnover.

- Communication and cooperation is necessary between the health department’s clinical, bioengineering and administrative departments, between the national health department and provincial hospitals, and with outside agencies.
This chapter describes how oxygen systems can be set up in a hospital ward. There is a description of an oxygen system in a children’s ward in an area designated for the sickest children, called a “high-dependency” area. This is where supportive care and close monitoring is available for the sickest patients. The chapter also discusses more specifically the planning and setting up of oxygen equipment within such an area. The general principles of establishing a high-dependency area are relevant whether the main source of oxygen is a concentrator, cylinders or oxygen piped from a central source. The chapter describes how to assess oxygen needs in an individual ward, how to identify appropriate equipment, the processes of procurement, installation and commissioning of oxygen concentrators, maintenance, training and safety issues. The general principles of how to organize oxygen systems in one area of a ward and the technical information on how to set them up is also relevant to emergency departments or adult medical or surgical wards.

12.1 The steps to planning and installing oxygen systems

Oxygen systems will be optimally effective if they are planned as part of an overall approach to improving quality of care within a hospital and a ward. A team approach is necessary, involving clinical staff, hospital administrators, engineers and trainers. Choosing the location, establishing a high-dependency area that is integrated within the ward, and ensuring there is sufficient technical expertise for day-to-day care, regular maintenance and safety of equipment are all crucial for oxygen to have a major impact on patient outcomes.

12.1.1 Assessing a hospital’s need for oxygen

A needs assessment should identify the equipment that is required for the particular ward or hospital. The number of beds in a ward to which oxygen should be available will depend on the total number of beds, the annual number of admissions, the proportion of patients admitted who have hypoxaemia, and the average duration of hypoxaemia. Some of this information, particularly the proportion of admissions with hypoxaemia, and its duration, may not be available. In some hospitals where acute respiratory infection is the most common condition, it has been found that 20–40% of admitted children will have hypoxaemia. In other hospitals where acute respiratory infection is less common, the proportion of children with hypoxaemia is less (2–10%). The average duration of hypoxaemia in children with pneumonia is about 2–3 days, although some studies, particularly in hospitals at higher altitude, have found an average of up to 5 days.

As a guide, for every 10–15 beds in the ward, at least one oxygen concentrator capable of delivering oxygen to four children at any one time will be required. Each ward will need one pulse oximeter to measure blood oxygen levels and enough sensor probes to last several years (about two per year).

There has been less research to support methods for determining oxygen requirements in adult internal medical, surgical and obstetric wards, but oxygen should be available in each of these wards, and in the emergency department. A short audit of oxygen needs may be necessary to plan effectively.
12.2 Organizational considerations

There are several things to consider from an organizational point of view, including where to make oxygen available, the actual oxygen system and whether or not to include a high-dependency ward in the hospital.

12.2.1 Location of oxygen systems

Oxygen and pulse oximetry should be available wherever seriously ill patients are managed. This includes the emergency department, operating theatres, adult medical, surgical and obstetric wards, paediatric wards and the special care nursery (neonatal ward). Many large and medium-sized hospitals will have an adult intensive care unit or high-dependency ward, where critically ill adults with medical, surgical or obstetric conditions are nursed. For seriously ill children in district hospitals, however, the best place of care will generally be in a high-dependency area within the children’s ward, not within adult wards or the adult intensive care unit. A separate area for neonates that has oxygen, pulse oximetry, apnoea monitoring and facilities for maintaining babies’ temperature will be optimal.

12.2.2 Oxygen systems as a foundation for improving quality of care

Leading a hospital in improving and ensuring quality of clinical care is the function of medical administrators and senior clinicians. Establishing an effective system to administer oxygen can substantially improve the overall quality of care that is provided in a hospital ward. Not only is oxygen essential in the management of many seriously ill patients, but the process of planning, setting up and maintaining an oxygen system within a high-dependency area encourages staff to make improvements to other key aspects of clinical care. This involves identification of the sickest patients, adoption of guidelines and protocols, a greater focus on monitoring, and attention to management issues such as ordering of consumables, maintenance of equipment, equipment safety and infection control. Establishing a good quality oxygen system and high-dependency care requires involvement and commitment from nurses, doctors, hospital engineers and administration staff.

12.2.3 A high-dependency area for care of the sickest patients

The high-dependency area should be close to the nursing station. All beds should have oxygen (see Figure 12.2). Children with the following conditions should be nursed there:

- hypoxaemia
- coma or severe seizures
- shock, sepsis or severe dehydration
- severe anaemia requiring a blood transfusion.

The criteria will depend on the size of the ward and the nursing capacity, but the aim is to have nurses focus additional attention on the children in the high-dependency area. In most hospitals the children’s high-dependency area should ideally be within the children’s ward, as there will be a necessary flow of children from the high-dependency area to a non-high-dependency area or general beds, and some children in the general beds will deteriorate, needing oxygen or a higher level of monitoring. In a busy district or provincial hospital with limited resources it is essential that after children improve they are moved to non-high-dependency area beds to make space for other children. If a high-
dependency area or intensive care unit (ICU) is in a separate ward this often does not happen smoothly or in a timely manner. Another reason for an integrated children’s ward high-dependency area is to maintain paediatric health workers in the one ward, and to build capacity in management of seriously ill children across all categories of staff. This will optimize overall nurse:patient ratios, rather than have the nursing capacity split with limited sharing of staff between wards. The essential components of a children’s ward high-dependency area are shown in the box below.

The basic essentials of a children’s ward high-dependency area

- oxygen to all beds
- pulse oximeter and sensor probes
- monitoring charts
- intravenous (IV) fluid administration sets (IV poles, fluid, giving sets, intravenous cannulae, etc.)
- guidelines for:
  - which children should be nursed in the high-dependency area
  - management of common diseases, e.g. WHO Pocketbook of hospital care for children
  - use of pulse oximetry (Annex A)
  - use of oxygen concentrator or cylinders (Annexes B and C)
  - safe administration of blood products
  - local drug compendium
- blood glucose monitor
- sharps disposal container
- sphygmomanometer
- equipment cupboard
- bookshelf for reference books
- electricity outlets
- hand basin and tap
- signs:
  - “No smoking”
  - “Wash your hands before and after touching patients”
- resuscitation trolley

The number of beds required in a high-dependency area is related to the number of admissions and the proportion of admissions with very severe disease; a rough estimate is provided in Table 12.1. Table 12.2 provides a rough estimate of oxygen resources required in a neonatal ward of a provincial or district hospital.

Oxygen should still be available in beds adjacent to the high-dependency area, for stable children still requiring oxygen.

Table 12.1  Estimate of oxygen resource needs in a high-dependency area of a children’s ward in a provincial or district hospital

<table>
<thead>
<tr>
<th>Number of annual pediatric admissions</th>
<th>Number of beds in children’s ward</th>
<th>Number of beds in the high-dependency area</th>
<th>Total number of beds with oxygen on the children’s ward (including those in the high-dependency area)</th>
<th>Number of pulse oximeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>15–30</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>30–60</td>
<td>6</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>60–80</td>
<td>8</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>3000</td>
<td>80–100</td>
<td>10</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>4000</td>
<td>80–120</td>
<td>15</td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 12.2  A high-dependency area in a children's ward
Table 12.2 Estimate of oxygen resource needs in a neonatal unit of a provincial or district hospital

<table>
<thead>
<tr>
<th>Number of annual neonatal admissions</th>
<th>Number of cots in neonatal ward</th>
<th>Number of neonatal cots with oxygen</th>
<th>Number of pulse oximeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>15</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>

*a* Most newborns will room-in with their mothers; only the sickest will be admitted to the neonatal unit.

12.2.4 The place of intensive care for children

“Intensive care” can best be defined as the provision of prolonged mechanical ventilation via an endotracheal tube and other expensive technology. When countries have child mortality rates above 30 per 1000 live births, a major proportion of child deaths will be preventable or treatable by simple measures, such as immunization, primary care and good quality, but basic, curative services in hospitals. In these situations it does not make sense to spend vast resources on intensive care in tertiary institutions to which only a small proportion of children will have access, when simpler and cheaper life-saving treatments are not available to a substantial proportion of sick children.

The main argument against providing intensive care in high mortality areas is that this would divert scarce resources away from more effective, low-cost interventions. Following the principles of equity, countries and hospitals should ensure that highly cost-effective health interventions that will reduce mortality are available to the vast majority of children, before funding intensive care services.

There are, however, good practical and ethical arguments for providing selective postoperative intensive care services even where national or regional mortality rates are high. Many patients who have undergone surgery die for want of appropriate supportive care, including mechanical ventilation, in the first 24 postoperative hours. WHO suggests that facilities for intensive care should be available in any hospital where surgery and anaesthesia are performed, and has published standards for intensive care units in large referral hospitals, district/provincial hospitals and small hospitals in developing countries. These standards outline conditions that should be able to be managed, procedures that should be able to be performed, and personnel, drugs and equipment that are necessary. Where mechanical ventilation is available, there is a good basis for providing intensive care for some other selected non-surgical conditions, particularly neuromuscular paralysis after snake-bite, which is time-limited and likely to result in a good outcome if appropriate supportive care is provided.

Pre-existing conditions for the development of highly specialized paediatric intensive care are good vaccine services, good-quality primary and first-referral level care, under-5 mortality rates less than 30 per 1000 live births, availability of transportation, good access for the majority of the population and sufficient human resources. Until these are achieved, acute hospital clinical care should focus on improving triage, emergency care, supportive care (including oxygen, nutrition and safe administration of intravenous fluids), monitoring, discharge planning and follow-up, and not on mechanical ventilation or other high-technology interventions. These priorities are outlined in the WHO *Pocketbook of hospital care for children*, and are the principles of high-dependency care.
12.3 Identifying suitable oxygen equipment

Suggested specifications for oxygen concentrators, pulse oximeters and sensor probes are outlined in the Annexes D, E and F. Purchasing uniform equipment is important for ensuring the compatibility of spare parts, for uniformity of training and servicing.

12.3.1 Choosing an appropriate oxygen source

The technical options for simple oxygen systems and specifications for equipment in small hospitals in developing countries are described in detail in section B. The two main sources of oxygen currently used in such settings are portable concentrators (based at the bedside) and cylinders. Oxygen transported under high pressure through copper pipes from a bank of cylinders or a large oxygen concentrator (oxygen generator) are other ways, more commonly used in tertiary hospitals, but requiring much larger resources in set-up and maintenance. Different levels of personnel, resources and infrastructure may entail different choices of systems and methods of administering oxygen. A comparison of oxygen cylinders and concentrators as a basis for oxygen systems is described in Table 12.3.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Oxygen cylinders</th>
<th>Oxygen concentrators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power source required</td>
<td>No</td>
<td>Yes, continuously</td>
</tr>
<tr>
<td>Transport requirement</td>
<td>Regularly</td>
<td>Only at time of installation</td>
</tr>
<tr>
<td></td>
<td>By air only in chartered aircraft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy and costly to transport</td>
<td></td>
</tr>
<tr>
<td>Exhausitble supply</td>
<td>Yes, standard cylinders last 2–3 days at most with continuous use</td>
<td>No, continuous supply as long as power remains uninterrupted</td>
</tr>
<tr>
<td>Establishment equipment costs</td>
<td>Oxygen flow meter (about US$ 400) and regulator (about US$ 200) per cylinder, costs moderate</td>
<td>Moderate up-front equipment cost (about US$ 1000), plus installation and commissioning, training</td>
</tr>
<tr>
<td>Ongoing costs</td>
<td>Cylinder refill costs moderate (US$ 30) but frequent, costs of transport from refilling station to hospital</td>
<td>Small: electricity, maintenance</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Minimal</td>
<td>Moderate, both preventive maintenance and intermittent repairs; spare parts needed</td>
</tr>
<tr>
<td>Training</td>
<td>In-clinic use of oxygen and pulse oximetry, plus day-to-day trouble-shooting of cylinders and connectors</td>
<td>Additional recommended for preventive maintenance of concentrators, training for hospital engineers/technicians, clinical use of oxygen and pulse oximetry</td>
</tr>
</tbody>
</table>

Oxygen concentrators have been used successfully in many country programmes. As liquid oxygen and cylinders are expensive and difficult to transport, oxygen concentrators are now being used increasingly. The theoretically unlimited flow rate that can be generated, depending on the size of the concentrator, has enabled these machines to supply anything from a small clinic to a 1000-bed teaching hospital. Concentrators are an economical way to deliver oxygen, being much cheaper than oxygen cylinders, especially to remote areas and where transport is costly. An oxygen concentrator draws in room air and separates out the nitrogen, to produce a high concentration of oxygen.
Oxygen concentrators are designed for continuous operation and can produce oxygen 24 hours a day, 7 days a week for up to 40,000 hours (about 5 years). Details of oxygen concentrators suitable for district and provincial hospitals are summarized in Table 9.3.

Design and manufacture of oxygen concentrators continue to improve, resulting in smaller, lighter and cheaper models. Generic specifications are available in Annex D and should be applied to currently available models when purchasing oxygen concentrators. New models of oxygen concentrators appear every year. However, within a hospital or health service, standardizing on one model helps ensure continuity and uniformity of spare parts, maintenance and training.

Oxygen concentrators need a continuous power supply, most commonly a reliable mains electricity source and a back-up generator in case of power failure. Solar power has been used at some hospitals to power oxygen concentrators.\(^7\)\(^9\) Set-up costs were high and 6 hours of sunlight per day was necessary to power the concentrator.

A universal power supply (UPS) machine can make electrical equipment more reliable in settings where power is unreliable. However, it is important to note that a UPS only provides power for a few minutes after the mains power goes off, which allows time for a switch to an alternative power source, such as a generator. A UPS can also protect concentrators and oximeters from power surges. UPS devices are expensive.

*Medical* oxygen is very expensive in many developing countries. For instance, in Papua New Guinea, with bulk purchase of large (7600-litre) cylinders, a continuous flow of 1 litre/minute of oxygen costs approximately US$ 6 per day, or US$ 2190 per year. This price does not include the cost of transport, which is considerable for rural areas, and it may be even greater if small orders are placed or small cylinders are used. For example, it costs US$ 14 per day or US$ 5110 per year for a continuous flow of 1 litre/minute from 440-litre cylinders purchased in bulk. A theoretical cost comparison of oxygen from cylinders and from concentrators in Papua New Guinea found significant cost savings with the latter, ranging from 25% in the smallest hospitals to 75% in large district hospitals.\(^8\)^\(^3\)

*Industrial* oxygen is often much cheaper than medical oxygen and may be easier to obtain. The principle of manufacture is identical to that of medical oxygen, and chemical impurities are unlikely in either form. Industrial oxygen is therefore usually safe for medical use and can be used instead of medical oxygen. If oxygen is obtained from an industrial source, however, hospital administrators or people in charge of oxygen supplies must confirm with the manufacturer that the cylinders do indeed contain oxygen and have not previously been used for other gases. The means of cylinder identification must be agreed with the supplier before cylinders are purchased.

Oxygen cylinders are heavy and difficult to transport. The cylinders have to be transported back to the bulk supply depot to be refilled, and back to the point of use. Transport is often unreliable in developing countries, and expensive, so there are often long periods when small hospitals in developing countries have no supplies of oxygen.

Oxygen cylinders have an important role in health facilities where there is no power supply, or where power supply is unreliable. Even in hospitals that use concentrators as the primary source of oxygen, having a cylinder of oxygen as a back-up in case of power failure is safe. Delivery of oxygen from an oxygen cylinder is shown in Figure 10.1.
In many larger hospitals, oxygen is distributed through a system of copper pipes from a central source of oxygen, usually located outside the building. These are described in detail in section 10.2.

12.3.2 Choosing an appropriate pulse oximeter

Pulse oximetry is the most accurate non-invasive method of detecting hypoxaemia. Various sizes of pulse oximeter are appropriate for district hospitals, from very small hand-held devices to machines about the size of a portable laptop computer (“bench-top” devices). In many hospital wards where resources are limited, only one pulse oximeter will be available. It is important that oximeters are portable so that patients in any part of the ward can be monitored; although it is best to group together the sickest patients in one “high-dependency” area. Although the hand-held oximeters are cheaper than the larger models, their battery life is shorter and there is a greater risk of theft than with bench-top oximeters. Where theft of hospital equipment is a major risk, it may be sensible to secure the oximeter in one place within the ward, within reach of the sickest patients. An alternative is to have a locked chain securing the oximeter to a bracket on a wall or bench with the key kept by the nurse in charge of each shift.

Although some oximeters can also measure other physiological parameters such as blood pressure, electrocardiograph (ECG) and capnography (measurement of exhaled carbon dioxide), the simpler devices monitoring only blood oxygen saturation (SpO₂) and pulse rate have fewer attachments that need replacing over time, require much less training to use and are much less expensive.

Oximeters should have robust, hard plastic casing, and be resistant to knocks and vibration. Oximeter technology functions well at high altitudes. Most oximeters also function well in humid and hot environments. Oximeters should have a rechargeable internal battery with a life of at least 8 hours and an AC power adaptor.

Some oximeters have a visible plethysmographic wave, or other graphical display of the pulse wave detected by the sensor probe. The wave is displayed either as a sine wave representing the pulse contour, or as a liquid crystal light that moves (vertically or horizontally) with every pulse. Monitoring the shape of this pulse wave helps health workers to ascertain the accuracy of the SpO₂ reading. If an oximeter does not have such a plethysmographic display, the pulse rate displayed by the oximeter must be checked with the patient’s pulse to ensure the readings are accurate.

For more details on specifications of oximeters and sensors that are suitable for use in a district hospital, see section 5.2 and Annex E.

12.4 Principles of buying oxygen equipment

Before purchasing any oxygen system and associated equipment, WHO recommends considering the following points.

- International standards and WHO recommendations are useful in ensuring that the equipment purchased is appropriate for the setting and that it will last.
- Complying with international standards and WHO recommendations may mean buying more expensive equipment, but will ensure long-term cost effectiveness.
- Buying uniform equipment allows common knowledge of the technology to accumulate and be passed on.
12.5 Implementing new technology for oxygen therapy

Successful implementation of oxygen therapy technology includes:

- having a “team approach” that builds local capacity – important when introducing new technology
- training and support in technical aspects and clinical use of the technology
- communicating with staff using the equipment
- continuous monitoring of training levels; ongoing training in the use of oxygen equipment, preventive maintenance and repair as needed.

12.6 Sending or receiving donations of equipment

WHO recommends the following principles for external donations.

- Donations should ensure maximum benefits to the recipients
- Donors should respect the wishes and context of the recipients
- Avoid double standards: donated equipment should not be inferior to what would be acceptable in the donor country
- There should be effective donor–recipient communication and planning.

Some major problems identified in donations of oxygen concentrators include:

- No spare parts
- No information
- Wrong frequency or wrong voltage
- No local engineering support

12.7 Installing and commissioning of oxygen concentrators

Installation and commissioning of oxygen concentrators is described in detail in section 9.1. Oxygen concentrators meeting WHO specifications are normally supplied with user and maintenance manuals which explain how the apparatus works and the limits of performance. The instructions should be read carefully by people installing the equipment, usually the hospital engineer.

12.8 Safety of oxygen equipment

It is the administrator’s role to ensure that staff understand the importance of oxygen equipment safety and that sufficient training and resources are available to ensure the safety of patients and staff.

Oxygen can cause fire to spread rapidly. Install “no smoking” signs in the ward, and tell parents and visitors that smoking is strictly forbidden in the ward, because of the fire hazard and the risk of passive smoking to patients. Keep anything that might create a spark or flame, such as portable heaters, stoves and electrical appliances, well away from concentrators, cylinders and tubing; a distance of 1.5 m is considered safe. Do not use oil or grease on cylinders and concentrators, because if these substances are present with oxygen the fire risk is greatly increased. Do not use an oxygen concentrator if either the power supply cable or plug is damaged. Immediately replace damaged cables or plugs. In
case of fire, switch off the oxygen flow immediately. To reduce fire risk, turn the oxygen source off when not in use. Firebreak connectors are recommended which will stop the oxygen flow in the event of fire.

Oxygen cylinders are large heavy objects that could seriously injure a child if the cylinder fell over; install them securely, using a strap or chain to fix them to the wall.

12.9 Maintenance of oxygen concentrators

Weekly maintenance of oxygen concentrators can be easily done by a nurse or assistant, and requires no special training other than being shown how to correctly remove, wash, dry and replace the external filter. Note that if the concentrator is in a dusty environment, this may need to be done more frequently, perhaps twice a week.

Maintenance of concentrators by engineers is described in detail in section 9.5. Training of hospital engineers in basic concentrator maintenance can be done in a 4–5-day course conducted by an expert in the field, or by a service representative from the manufacturer.

12.10 Training in oxygen systems, use, safety and maintenance

It is the administrator’s role to ensure that those installing and using the equipment have sufficient training and resources to carry out their roles. It is essential that nurses and doctors are trained in the clinical use of oxygen and day-to-day maintenance and care of equipment, and that hospital engineers are trained in routine maintenance and repair.

Training should cover the areas described in Table 12.4 below. Ideally, training for clinical staff in the use of oxygen should be part of an overall programme to improve the quality of care for children. The WHO Pocketbook of hospital care for children provides evidence-based guidelines for hospitals with limited resources. The guidelines are consistent with the integrated management of childhood illness (IMCI), the primary care case-management strategy. Training tools for the WHO Pocketbook of hospital care for children include a CD-ROM (which includes a video on the clinical use of oxygen and case-based teaching on acute respiratory infection) and the Emergency Triage Assessment and Treatment course (which focuses on emergency management).

<table>
<thead>
<tr>
<th>Table 12.4 Training for clinicians and hospital engineers</th>
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<tr>
<td>Training for nurses, doctors and other clinical officers</td>
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<td>Methods for detection of hypoxaemia</td>
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<td>What is pulse oximetry and how to use it?</td>
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<td>Oxygen concentrators and how they work</td>
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<td>Equipment care and maintenance, safety issues</td>
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Training for hospital engineers

| The importance of hypoxaemia | Chapter 1 |
| Oxygen concentrators and how they work | Chapter 9 |
| Equipment care and maintenance, safety issues | Chapter 9 |
| Pulse oximetry and how it works | Chapter 11, Annex A |
13 Principles of managing a national or regional oxygen programme

Good management of oxygen systems at a national or regional level is vital. In most administrative regions this will be combined with a programme for management and use of other medical and hospital equipment, and programmes of clinical and biomedical engineering training. Biomedical engineering expertise is important. Ideally this should be available within the ministry of health, but if not, it may be available through nongovernmental organizations, WHO or other United Nations agencies. Sourcing biomedical technical expertise through the private sector will increase the expense of such programmes markedly, but public–private partnerships may be appropriate in some countries.

Honest governance over equipment procurement and maintenance contracts is very important. Poor governance and corruption can result in programmes that are much more expensive than necessary. Corruption wastes life-saving resources and will diminish the confidence of health workers and the public in the health system. However, good governance, and systematic monitoring and evaluation of such programmes greatly enhance health worker and community confidence, and demonstrate that progress can be made. This should be the aim, acknowledging that every aspect cannot be achieved at once.

In hospitals and large health clinics, oxygen needs to be available at all times. In making oxygen continuously available to patients who need it, the choice of equipment and ways to use it will be influenced by the personnel and infrastructure that are available. The equipment cannot stand alone: it always needs people to understand, operate and repair it, and supplies and spare parts to keep it working. Technical information is included in the previous sections.

Figure 13.1 lists some of the key considerations of a national oxygen programme. Some of these are relevant at a hospital clinical or administrative level and some are relevant at a ministry of health level.
13.1 What have other countries experienced when implementing oxygen systems

Establishing oxygen delivery systems in hospitals with limited resources can be challenging. This section provides case studies of six countries’ experiences in improving oxygen delivery, which highlight the need to evaluate the adaptability of new technology to specific settings.

- Oxygen concentrators can offer cost savings and help overcome limitations of oxygen supply, particularly in settings with high oxygen demand.
- Oxygen concentrators require a reliable power source, so ensuring back-up generators or oxygen cylinders are available is important in areas with unreliable power supply.
- Appropriate application of oxygen technology has the potential to significantly improve health outcomes.
- The unlimited supply provided by oxygen concentrators encourages an increase in the use of oxygen.
- Where technical expertise is available in remote facilities without regular electricity, using solar power can offer a cost-effective and reliable supply (see Figure 13.2). Solar power systems will need to include solar panels, batteries, a charge controller and an inverter. They are high in capital costs but cheap to run and can be cost effective if properly designed and maintained.
13.1.1 Egypt

Implementing and supporting new technology in district hospitals

In 1993, a project was set up to introduce oxygen concentrators in upper Egypt. This involved installing oxygen concentrators in district hospitals, training of technicians in installation and maintenance, making regular inspections, servicing and repairing the equipment and setting up a reporting system that would closely inspect the performance and usefulness of the machines. A team and an overall coordinator were appointed to carry this out. One year after installation, two concentrators out of a total of 22 had faults and both were repaired. The training of staff was successful and the day-to-day running of the programme was predominantly done by the local team.85

13.1.2 Papua New Guinea

Clinical impact of better detection of hypoxaemia and improved oxygen supply

After studies showed that hypoxaemia was a major child health problem and that the supply of oxygen was a major problem in Papua New Guinea,6;16 pulse oximeters and oxygen concentrators were introduced in five hospitals in 2005. Nurses, doctors and engineers/technicians were provided with appropriate training in the use, maintenance and repair of the equipment. The technology, training and ongoing support formed the oxygen programme in Papua New Guinea.86

In the following two-and-a-half years, there was a highly significant reduction in hospital mortality rates for pneumonia. In the years before the system was introduced, there were 356 deaths from 7161 admissions for pneumonia (case fatality rate 4.97%). In the two-and-a-half years after the system was introduced, there were 115 deaths from 3538 admissions (case fatality rate 3.2%). The risk of a child with pneumonia dying in the hospitals after the system was introduced was 35% lower than before, risk ratio 0.65
(95% confidence interval, 0.53–0.80), \( P < 0.0001 \). This programme has now been extended to 17 hospitals.

13.1.3 Malawi

A large national Child Lung Health programme

Malawi was one of the first countries with limited resources to implement a national oxygen programme, beginning in 2002. This was part of a highly successful National Child Lung Health Project. Case fatality rates from pneumonia have consistently fallen since the introduction of the programme. In 2007, an evaluation of 15 hospitals using oxygen concentrators showed that this technology had been successful in reducing hospital mortality for pneumonia. Many units of one particular model, which claimed to comply with international standards, were not working. This emphasizes that the cheapest equipment will not always be the most cost-effective in the long term, and that manufacturers' claims need to be tested in the field. One challenge was high staff turnover, partly due to migration and many staff being unwell with the human immunodeficiency virus, making it difficult to sustain adequate staff skill levels. Another challenge to optimal success is user fees; making hospital care free for children in one hospital markedly increased demand and access, compared with hospitals in which fees were charged.87

13.1.4 Nigeria

Oxygen concentrators in a neonatal unit

Oxygen concentrators were introduced to a neonatal unit in 1993 to overcome the limitations of cylinder oxygen. A model that met international standards was purchased and installed. It ran for 18 hours a day for 3 years without breaking down, despite high daily temperatures (30–32 °C) and very dusty conditions. The cost of treating one patient for one year using the concentrator was 27% that of using cylinders. Greater cost savings could have been achieved if a flow splitter was used on the concentrator, so that multiple patients could have been treated at once. The use of the concentrator was limited by interruptions to the power supply. During power cuts, a portable generator or a car battery with an inverter were used to power the concentrator.88

13.1.5 Nepal

Oxygen concentrators at high altitude

Oxygen demands are high at the Kunde hospital, located near Mt Everest, 3900 m above sea level. Oxygen is required for childbirth, neonatal resuscitation, surgical procedures and management of cardiopulmonary illness and altitude sickness (e.g. high altitude pulmonary or cerebral oedema). It is a 10-day walk from the nearest road, and transport of cylinders is difficult. In 1997, oxygen concentrators were installed, and connected to power supplied by a hydroelectric system with a petrol generator as a back-up. An additional two concentrators are kept as back-up. No equipment failures had occurred over 3 years, and the concentrators have replaced oxygen cylinders and portable hyperbaric chambers.89

14.1.6 The Gambia

Donations and solar power

In 2000, a teaching hospital in the Gambia received a donation of oxygen concentrators. Unfortunately, very quickly, all the equipment stopped working. The main problem was
lack of compatibility of frequency: machines constructed for use with 110V 60Hz electrical supply did not function with the 230V 50Hz local electrical supply. The concentrators were second-hand, and although they had been serviced before donation, no-one in the Gambia had the expertise to maintain the equipment, and the donor did not assess whether the frequency was compatible. This emphasizes the need for better planning, management and local participation around equipment donations in developing countries. It is also important to ensure that any new equipment, donated or bought, meets WHO standards and is supported by sufficient technical expertise. Following this experience, the hospital organized a donations committee to oversee all donations, working with a nongovernmental organization partner.84

In a remote district hospital without regular electricity in the Gambia, oxygen concentrators were run successfully on solar power. Despite a high initial cost, the running costs were minimal. Such a set-up requires an even higher level of technical expertise, but can be very cost effective.79
Part III Annexes
Annex A Guidelines for the use of pulse oximetry in children’s wards

A pulse oximeter can tell you vital information about a sick child. It is the best way to tell if a child needs oxygen, but it is vital to also look for clinical signs of hypoxaemia and severe illness.

See also Annex B (Guidelines for the administration of oxygen using oxygen concentrators) or Annex C (Guidelines for the administration of oxygen using oxygen cylinders).

A.1 When to use a pulse oximeter

Pulse oximeters should be used to monitor:

- every child or neonate at admission (not just those with pneumonia)
- all children at the time of admission to the ward
- the progress of children, during ward rounds and nursing observations
- any child who deteriorates with respiratory distress, apnoea or decreased consciousness state.

A.2 Using a pulse oximeter

To use a pulse oximeter:

1. Turn the pulse oximeter on.
2. Have the child sitting comfortably in the parent’s lap.
3. Attach the oximeter probe to the finger or toe of the child.
4. Wait until there is a consistent pulse signal (this may take 20–30 seconds).
5. Record the SpO2 on a monitoring chart.
6. If the SpO2 is <90% the child should receive oxygen.
   - through nasal prongs or a nasal catheter
   - at a flow rate of 0.5–2 litres/minute continuously.
7. Recheck the SpO2.
8. Record the SpO2 on a monitoring chart 15 minutes after giving oxygen.

A.3 Daily monitoring using pulse oximetry

At least once a day, all children who are receiving oxygen should be tested using pulse oximetry:

1. Take the child off oxygen (unless they have severe respiratory distress).
3. If the SpO2 >90% 10–15 minutes after coming off oxygen, leave off oxygen.
4. Check the SpO2 again in one hour.
5. If the SpO₂ is <90%, resume oxygen.

6. Each day, record the SpO₂ on the patient’s monitoring chart, and beside it record if there are sufficient supplies of oxygen.

7. Oximetry should be used regularly to monitor any child who develops worsening respiratory distress, apnoea, any deterioration in consciousness or any other clinical sign of deterioration.

A.4 Discharge planning

Pulse oximetry can be used to determine when it is safe to send a child home. In most circumstances it is not safe to send a child home when their SpO₂ is <90%.

A.5 Care of a pulse oximeter

The pulse oximeter finger probes and leads are fragile, so it is important to look after them carefully. They should not be put on the floor or where they could be stepped on.

It is important to keep pulse oximeter probes clean so that they do not spread infection from one patient to another. They should be wiped with an alcohol swab between patients, and health workers must always wash their hands before and after monitoring each patient.

Always remember to plug the oximeter into the mains power at regular intervals to recharge the internal battery.
**Annex B Guidelines for the administration of oxygen using oxygen concentrators**

Low oxygen levels (hypoxaemia) are common in sick children and newborns. Hypoxaemia is a common cause of death. The best way to detect hypoxaemia is with a pulse oximeter, which measures blood oxygen levels. If this is available in your hospital, see Annex A (Guidelines for the use of pulse oximetry in children’s wards).

If pulse oximetry is not available, hypoxaemia can also be detected by simple clinical signs and treated with oxygen, from either oxygen concentrators or oxygen cylinders. The following clinical signs indicate hypoxia:

- central cyanosis (blue colour of the tongue or gums)
- fast or difficult breathing and inability to feed
- severe chest indrawing
- grunting with every breath, nasal flaring or head nodding.

If a child has any of the above signs of hypoxaemia they should receive oxygen.

![Figure B.1 Signs of hypoxaemia in a child](image)
B.1 **Oxygen concentrators**

Oxygen concentrators are machines that extract nitrogen from atmospheric air, resulting in an output of almost pure oxygen.

Oxygen concentrators need a continuous and reliable power source, such as mains electricity plus a back-up generator or oxygen cylinder in case of power failure.

B.2 **How to use an oxygen concentrator**

Follow the steps below to use an oxygen concentrator:

1. Position the concentrator so that it is at least 30 cm away from walls or curtains, so that the inlet opening at the back is not obstructed.
2. Connect oxygen tubing to the flow splitter or oxygen outlet.
3. Plug the power cord into the mains electricity supply.
4. Turn on the concentrator (switch on the console). A green light on the concentrator should come on when a sufficiently high oxygen concentration is reached, usually within 10 minutes.
5. Adjust the flow meter according to the flow required for the patient, or if using a flow splitter, the number of patients receiving oxygen.

B.3 **Routine maintenance**

On a weekly basis an oxygen concentrator will require approximately 30 minutes of attention. Concentrators have a large particulate filter over the air inlet opening (usually at the back of freestanding or portable models). This filter stops dust and other airborne particles from entering the unit. The filter should be removed and cleaned in warm soapy water, dried with an absorbent towel and replaced.

The exterior of the oxygen concentrator should be cleaned with a mild disinfecting cleaning agent or a diluted solution of bleach (5.25% sodium hypochlorite). A solution in the range of 1:100 to 1:10 of bleach to water can be used effectively, depending on the amount of organic material present. Allow the solution to remain on the surface for 10 minutes and then rinse off and dry.

B.4 **Giving oxygen**

Oxygen is usually given by nasal catheter or nasal prongs.

B.4.1 **Nasal catheter**

A 6-F or 8-F catheter is passed for a distance that is equal to the distance from the side of the nostril to the inner margin of the eyebrow (see Fig B.2). This usually reaches the back of the nasal cavity. Set a flow rate of 0.5 litre/minute (newborns) and 1–2 litres/minute (infants and older children). Humidification is not required with a nasal catheter, if these flow rates are used. If an oxygen catheter is not available, a nasogastric tube with the end cut off is sufficient (and cheaper).

Catheters should be removed and cleaned twice a day, as they can become blocked with mucus.
B.4.2 Nasal prongs

In some hospitals nasal prongs will be available. These should be placed just inside the nostrils and secured in place with tape, as shown in Figure B.3. Set a flow rate of 0.5–1 litres/minute (newborns), 1–2 litres/minute (infants and older children), up to a maximum of 4 litres/minute for preschool and school-aged children. Humidification is not required when using nasal prongs, as long as these flow rates are used.

Oxygen prongs are more expensive than oxygen catheters, but they can be reused if they are carefully soaked in clean, warm, soapy water, followed by dilute bleach, rinsing in water and careful drying.
B.5 Monitoring

After starting a child on oxygen, recheck the oxygen saturation using an oximeter or check for signs of hypoxaemia.

If, after starting on oxygen, the child still has an SpO₂ <90% or has cyanosis or severe chest indrawing, increase the oxygen flow to a maximum of 2 litres/minute in an infant or up to 4 litres/minute in an older child. If, despite this, the child still has signs of hypoxaemia check that:

- the concentrator is delivering a flow of gas
- the light indicating adequate concentration of oxygen is on, and that no other alarms are on
- oxygen is flowing from the catheter or prongs (put the end under water in a beaker and watch for bubbles, or hold the end close to your hand to feel the airflow)
- there are no leaks in the connections or the oxygen tubing
- the child’s nose is not blocked.

Do not use flow rates greater than 2 litres/minute in newborns and infants as this can result in distension of the stomach. Any infant who is unable to suck, or who needs an oxygen flow of 2 litres/minute, should have a nasogastric tube to decompress the stomach.

If the SpO₂ remains <90% or signs of hypoxaemia persist, the child may need a second source of oxygen, such as high-flow mask oxygen, if it is available. Also consult your hospital engineer to check the functioning of the concentrator.

B.6 Oxygen is highly flammable

It is very important not to allow an open flame or a cigarette anywhere within 3 m of an oxygen source. Install “No smoking” signs wherever oxygen is used.
Low blood oxygen levels (hypoxaemia) are common in sick children and newborns. Hypoxaemia is a common cause of death. The best way to detect hypoxaemia is with a machine called a pulse oximeter, which measures blood oxygen levels. If this is available in your hospital, see Annex A (Guidelines for the use of pulse oximetry in children’s wards).

Hypoxaemia can also be detected by simple clinical signs (some of which are illustrated in Figure C.1) and treated with oxygen. The following five clinical signs indicate hypoxaemia:

- central cyanosis (blue colour of the tongue or gums)
- fast or difficult breathing and inability to feed
- severe chest indrawing
- grunting with every breath, nasal flaring or head nodding.

If a child has any of the above signs of hypoxia they should receive oxygen.

Figure C.1 Signs of hypoxaemia in a child
C.1 Oxygen cylinders

Cylinders contain compressed gaseous oxygen. Cylinders need three things: a regulator that limits the pressure of oxygen being released, a gauge to indicate the amount of oxygen in the cylinder, and a flow meter to control oxygen flow to the patient.

When using an oxygen cylinder:

- Tighten all connections so oxygen does not leak (there are connections between the cylinder and the regulator, and between the regulator and the flow meter).

- Open the regulator and check the amount of oxygen in the cylinder on the pressure gauge. If the needle of the gauge is in the red zone the cylinder is nearly empty and should not be used unless that is the only cylinder you have. Never allow such a cylinder to be used on a child overnight, as it will run out and the child will become hypoxaemic.

C.2 Giving oxygen

Oxygen is usually given by nasal catheter or nasal prongs.

C.2.1 Nasal catheter

A 6-F or 8-F catheter is passed for a distance that is equal to the distance from the side of the nostril to the inner margin of the eyebrow. This usually reaches the back of the nasal cavity (see Figure C.2). Set a flow rate of 0.5 litre/minute (newborns) and 1–2 litres/minute (infants and older children). Humidification is not required with a nasal catheter if these flow rates are used. If an oxygen catheter is not available, a nasogastric tube with the end cut off is sufficient (and cheaper).

Catheters should be removed twice a day and cleaned as they can become blocked with mucus.

Figure C.2 Nasal catheter in place
C.2.2 Nasal prongs

In some hospitals nasal prongs will be available. These should be placed just inside the nostrils and secured in place with tape, as shown in Figure C.3. Set a flow rate of 0.5–1 litre/minute (newborns), 1–2 litres/minute (infants and older children), up to a maximum of 4 litres/minute for preschool and school-aged children. Humidification is not required when using nasal prongs, as long as these flow rates are used.

Oxygen prongs are more expensive than oxygen catheters, but they can be reused if they are carefully soaked in clean, soapy water, followed by dilute bleach, rinsing in water and careful drying.

Figure C.3 Nasal prongs

C.3 Monitoring

After staring a child on oxygen, recheck the oxygen saturation using an oximeter and/or check for the signs of hypoxaemia.

If, after starting on oxygen, the child still has an SpO₂ <90% or has cyanosis or severe chest indrawing, increase the oxygen flow to a maximum of 2 litres/minute in an infant or up to 4 litres/minute in an older child. If, despite this, the child still has signs of hypoxaemia check that:

- the cylinder has sufficient oxygen
- oxygen is flowing from the catheter or prongs (put the end under water in a beaker and look for bubbles, or hold the end close to your hand to feel the airflow)
- there are no leaks in the connections or the oxygen tubing
- the child’s nose is not blocked.

Do not use flow rates greater than 2 litres/minute in newborns and infants as this can result in distension of the stomach. Any infant who is unable to suck, or who needs an oxygen flow of 2 litres/minute, should have a nasogastric tube to decompress the stomach. If the SpO₂ remains <90% or signs of hypoxaemia persist, the child may need a second source of oxygen, such as a high-flow mask, if it is available.
C.4 Supply of oxygen cylinders

It is important to monitor the amount of oxygen in the cylinder. If the gauge is in the red zone then the bottle will need changing soon. Never allow such a cylinder to be used on a child overnight, as it will run out and the child will become hypoxaemic.

You must anticipate the need for oxygen and order more before it runs out.

C.5 Oxygen is highly flammable

It is very important not to allow an open flame or a cigarette anywhere within 3 m of an oxygen source. Install “No smoking” signs wherever oxygen is used. Firebreak connectors are recommended which will stop the oxygen flow in the event of fire.
Annex D  Procurement of oxygen concentrators and spare parts

Many models of portable oxygen concentrators currently manufactured are primarily intended for use in the homecare market for adults with chronic lung disease. The Standard ISO 8359:1996 is specifically aimed at such machines. The notes and questionnaire below will help identify additional requirements that will assist in the procurement of oxygen concentrators for patient care in a hospital.

The manufacturer should provide information on the total capital cost over a period of 40 000 hours including replacement filters and spare parts, is required.

Operating efficiency is defined in terms of litres of oxygen produced per kilowatt hour: a minimum value of 800 litres/kilowatt hour is suggested.

D.1  Notes on the oxygen concentrator procurement questionnaire

The following points should be kept in mind when using the questionnaire.

- Models are typically available for 240 V/50 Hz, 240 V/60 Hz or 120 V/60 Hz. The expected range of voltage variation should also be indicated.
- Some manufacturers recommend the use of a voltage regulator, and if so, the cost of this device should be established.
- Most 5 litres/minute concentrators use about 350 W. This parameter is important for the calculation of efficiency.
- Most manufacturers quote the maximum flow for a concentration of 90 ±3% (i.e. a minimum concentration of 87%).
- There are surprisingly large variations in the efficiency of oxygen production by concentrators. Based on a review of models on the market in 2003, the range of efficiency was 667–1170 litres/kilowatt hour. This points to a large variation in the running costs for concentrators. A minimum value of 800 litres/kilowatt hour is suggested.
- Most concentrators have an oxygen output of 4 or 5 litres/minute with one flow meter and one concentrator outlet, so with a 4-way flow splitter fitted, four infants can be supplied. Some have two flow meters and two concentrator outlets with a total flow of 8 litres/minute and so can be used to supply eight patients using two flow splitters.
- Flow indicators may be ball flow meters or multiple, fixed orifices. There is a specification for their accuracy in ISO 8359:1996.
- It is not uncommon to find that the range of the flow meter exceeds the maximum flow specified by the manufacturer for the output of the concentrator, so that it is possible to set excessively high flows. In such situations excessive flows can damage the sieve beds irreversibly. It is therefore desirable to have a device fitted to the concentrator that limits the total flow which can be delivered. Only a few models have such limiting devices.
- Higher outlet pressure may be useful for operating devices such as nebulizers.
- A maximum weight of 25 kg is suggested for ease of handling.
• An hour meter is essential for monitoring use.

• Some machines are perceptibly noisier than others. The upper limit of 60 decibels (dBA) given in ISO 8359 is unacceptably high for ward use. There are some quiet machines on the market, but these tend to be less efficient and more expensive to buy.

• Operation at high altitude is important in some countries, especially those with health facilities above 2000 m. This parameter is also an indicator of the efficiency of the concentrator and so may also be relevant for countries that lie below 2000 m.

• Operation at the highest temperature is desirable; oxygen concentrators always run hot and may cut out if they overheat. It is suggested that concentrators should still function at a temperature of >40 °C.

• High humidity can cause problems for some concentrators, as water is easily retained by sieve beds; this then interferes with the separation of oxygen from nitrogen. Some concentrators have specifications that assume room air-conditioning. These are inappropriate for most hospitals in developing countries.

• A small generator may be worthwhile as a standby, but a better approach is to have an effective standby generator for the whole hospital.

• There are very large variations in the number and cost of filters specified as essential replacements by different manufacturers.

• All manufacturers should be able to give realistic figures for replacement parts needed over 40 000 hours. A stock of such parts may then be purchased to facilitate local repairs. Preventive maintenance on valves is very important. For some models such maintenance is required at intervals of 3–6 months. Other models use more reliable valves needing little or no maintenance.

• All models will need compressor maintenance or replacement during a lifetime of 40 000 hours. The service intervals, parts and costs for keeping the compressor running should be clearly stated by the manufacturer.

• A flow splitter can be used to divide the oxygen flow between (up to) four patients. Several different types of flow splitter have been used, which have different costs.

• Compliance with ISO 8359:1996 and IEC 60601-1 are essential. 75,77

• ISO 8359: 1996 requires that all oxygen concentrators have an oxygen concentration status indicator (OSCI), but some manufacturers still sell models which lack this essential device.

• The application of a CE mark implies that the manufacturer has a quality system that meets the requirements of the European Medical Device Directive and ISO 13485:2003. 90

• A comprehensive service manual is essential.

• The cost of an extended warranty needs to be carefully evaluated.

• The supply route for spare parts should be made clear before purchase of a concentrator.

• Technical training in the country for local technicians is an essential part of this purchase and should be costed.
**D.2 Procurement questionnaire for oxygen concentrators**

<table>
<thead>
<tr>
<th>Question</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What voltage does the device operate at? Is it 240 V/50 Hz, 240 V/60 Hz or 120 V/60 Hz? (Specify your local power supply.)</td>
<td></td>
</tr>
<tr>
<td>2. Is a voltage system regulator required? If so what is the cost?</td>
<td></td>
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<tr>
<td>3. What is the maximum flow for each outlet?</td>
<td></td>
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<tr>
<td>4. What is the maximum wattage? (Should not exceed 350 W for a 5 litre/min output or 600 W for a 10 litre/min output)</td>
<td></td>
</tr>
<tr>
<td>5. What is the oxygen concentration at maximum flow?</td>
<td></td>
</tr>
<tr>
<td>6. What is the efficiency (in litres/kilowatt hour) at maximum flow?</td>
<td></td>
</tr>
<tr>
<td>7. What is the number of outlets on the concentrator with individual flow controls/indicators?</td>
<td></td>
</tr>
<tr>
<td>8. Does the concentrator comply with ISO 8359:1996 clause 50.3?</td>
<td></td>
</tr>
<tr>
<td>9. What is the outlet pressure?</td>
<td></td>
</tr>
<tr>
<td>10. Is the concentrator fitted with a means to limit the total flow delivered so that it is not more than 1 litre/minute above the maximum flow specified?</td>
<td></td>
</tr>
<tr>
<td>11. What is the weight (kg)?</td>
<td></td>
</tr>
<tr>
<td>12. What are the dimensions (cm)?</td>
<td></td>
</tr>
<tr>
<td>13. Is there an hour meter to record total running hours?</td>
<td></td>
</tr>
<tr>
<td>14. What is the noise level?</td>
<td></td>
</tr>
<tr>
<td>15. What is the maximum operating altitude?</td>
<td></td>
</tr>
<tr>
<td>16. What is the maximum operating temperature?</td>
<td></td>
</tr>
<tr>
<td>17. What is the maximum operating humidity?</td>
<td></td>
</tr>
<tr>
<td>18. What generator is compatible? (List model and model number)</td>
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</tr>
<tr>
<td>19. How many replacement filters are required for 40 000 hours of operation? What do they cost in total?</td>
<td></td>
</tr>
<tr>
<td>20. What spare or replacement parts are required for 40 000 hours of operation (e.g. compressor, sieve beds, valve spares kits)? What would they cost?</td>
<td></td>
</tr>
<tr>
<td>21. Does the concentrator have a 4-way flow splitter which can deliver flows of 0.5, 1.0 and 2.0 litres/minute? What is the cost?</td>
<td></td>
</tr>
<tr>
<td>22. Does the concentrator comply with ISO 8359:1996?</td>
<td></td>
</tr>
</tbody>
</table>
23. Does the model include an oxygen concentration status indicator?

24. Does the concentrator comply with IEC 60601-1?

25. Does the concentrator carry a CE mark? Please provide a certificate.

26. Is there a user manual available? Please provide an electronic copy.

27. Is a service manual with a troubleshooting guide, circuit diagrams and parts list provided?

28. What is the duration of the warranty?

29. What are the cost and conditions of an extended warranty?

30. What is the route for supply of spare parts?

31. What technical training can be provided in this country?
The questionnaire below can be used by purchasing agencies such as national departments of health or nongovernmental organizations to identify current models of pulse oximeters that meet the clinical requirements of small hospitals in developing countries.

E.1 Notes on the pulse oximeter procurement questionnaire

The following points should be kept in mind when using the questionnaire.

- Pulse oximeters are inherently reliable electronic devices with a lifetime of at least 5 years. In the past, oximeter manufacturers have profited from the supply of sensors, which were either disposable or have had a short life.
- It is essential to buy a device in which mains power charges an internal battery. A minimum operating time of 8 hours on an internal rechargeable battery is recommended.
- Most models quote an accuracy range of ±2%. Accuracy below an SpO₂ of 70% is difficult to establish.
- Models with more features (capnography, electrocardiograph tracing) are more expensive than a basic model which displays SpO₂ and pulse rate, and probably are beyond the requirements for most district hospital wards in developing countries.
- New models of pulse oximeters with fewer features (no alarms, no plethysmograph) have recently appeared on the market from new manufacturers at low prices (around US$ 100–300). In general, these have not been tested in hospitals in developing countries.
- The date of introduction and the number manufactured give an indication of the market response and reliability of the device. The longer in production and the more sold the better.
E.2  Procurement questionnaire for pulse oximeters

Model name:                  Part number:

1. What voltage does the device operate at? Is it 240 V/50 Hz, 240 V/60 Hz or 120 V/60 Hz? (Specify your local power supply)

2. What is the cost?

3. What are the dimensions? (cm)

4. What is the weight? (kg)

5. What is the operating temperature range? (°C)

6. What is the range of operating humidity?

7. What is the accuracy for SpO2 in the range 70–100%?

8. What is the pulse rate range? (beats/minute)

9. Does the device operate via a rechargeable battery? What type?

10. What is the operating time on a fully charged battery? (hours)

11. Does the device have a plethysmograph display? What type of wave is displayed? (waveform, bar graph, other, none)?

12. What year was this model introduced?

13. Approximately how many have been produced?

14. Does the device have alarm limits for SpO2? High (yes / no); Low (yes / no)

15. Does the device have alarm limits for pulse rate? High (yes / no); Low (yes / no)

16. Does the pulse oximeter comply with ISO 9919:2005?

17. Does the pulse oximeter comply with IEC 60601-1?

18. Does the pulse oximeter carry a CE mark? (Please provide a certificate)

19. Is a user manual available? (Please supply an electronic copy)

20. Is a service manual supplied with the oximeter?

21. What is the duration of the warranty and conditions?

22. What is the cost of an extended warranty?

23. Provide details of the route for supply of spare or replacement parts.
Annex F  Procurement of pulse oximeter sensor probes

For many years the main expense in operating pulse oximeters has been the cost of replacing sensors. Problems with raising funds to replace defunct sensors have prevented widespread use of pulse oximeters in hospitals where resources are limited.

Several companies have now begun to supply reusable sensors with a guaranteed lifetime in the range of 9–15 months. The companies that manufacture such sensors typically are not manufacturers of pulse oximeters, but can supply sensors which work with nearly all pulse oximeters currently available. It is therefore now possible to specify the purchase of sensors with a defined cost for a period of 5 years. This situation enables reliable pulse oximetry to become widely available for a defined, low cost.

F.1 Procurement questionnaire for pulse oximeter sensor probes

Model name:  Part number:

1 What pulse oximeters are the sensors compatible with? (List model names and model numbers)

2 Is a finger clip sensor available for:
   • paediatric use
   • adult use

   If yes, state cost for each

3 What is the guaranteed lifetime of finger clip sensor (months)

4 Is a flexible “Y” sensor available for:
   • paediatric use
   • adult use

   If yes, state cost for each

5 What is the guaranteed lifetime of flexible “Y” sensor (months)

6 Is your company prepared to supply sensors for a fixed price and to give a guaranteed supply of sensors for 5 years?

7 How would the sensors be delivered?

8 Does your company carry out sensor repair? If “yes”, give details of repair cost.
The following resources are available from the website of the Centre for International Child Health, based at the Royal Children’s Hospital, Melbourne (http://www.rch.org.au/cich) under ‘links and resources’.

**Country experiences**

**PNG oxygen project** The clinical impact of improving oxygen systems in children's wards.

**Oxygen program in PNG** Technical and clinical experience with setting-up oxygen systems in Papua New Guinea.

**Oxygen supply in rural Africa** The costs incurred using oxygen cylinders compares with a solar operated oxygen concentrator in rural Gambia.

**Field trial of oxygen concentrators in upper Egypt** Setting up and testing oxygen concentrators.

**Hypoxaemia in children with severe pneumonia** A study in the highlands of Papua New Guinea.

**The Malawi anaesthetic machine** The performance and problems associated with a new oxygen concentrator and anaesthetic machine.

**Clinical resources**

**Pulse oximetry March 2009** A presentation outlining the application of pulse oximetry in clinical practice.

**WHO oxygen therapy** This 1993 review of oxygen therapy for children with acute respiratory infection in developing countries offers an overview of the historical basis for continuous oxygen therapy, the clinical indications, its initiation and a brief outline of oxygen equipment.

**Pulse oximetry review** A review of pulse oximetry and its applications in the medical management of childhood illnesses (published in Annals of Tropical Paediatrics).

**Review of hypoxaemia in childhood illness** A review of the prevalence of hypoxaemia in childhood illnesses, with emphasis on pneumonia and neonatal conditions (published in The Lancet Infectious Diseases).


**When should oxygen be given to children at high altitude?** A systematic review to define altitude-specific hypoxaemia (published in Archives of Disease in Childhood, access via ICHRC website, “Supportive care” section)
Technical resources

**Oxygen Assessment** *A WHO assessment tool for the evaluation of oxygen systems in children's wards.*

**Suitability of oxygen concentrator models** *for use as the primary source of oxygen in hospital wards.*


**International Union against Tuberculosis and Lung Disease**

The International Union against Tuberculosis and Lung Disease has a section on oxygen use in the Child Lung Health Project in Malawi [http://www.theunion.org/lch/technical-assistance.html](http://www.theunion.org/lch/technical-assistance.html)
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Ref Type: Report


Ref Type: Generic


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