CHAPTER

2

Administering Medical Gases

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OBJECTIVES

1. Describe the basic operation of single-stage and multistage regulators.
2. Describe the basic operation of a Thorpe tube flowmeter.
3. Compare pressure-compensated devices to non–pressure-compensated devices.
4. Describe the basic operation of a Bourdon gauge.
5. Discuss the operation and uses of oxygen blenders.
6. List the indications for and hazards of oxygen therapy.
7. Define low-flow oxygen therapy, list the devices that provide low-flow therapy, and state the flow and F_{IO_2} specifications for these devices.
8. Discuss how the F_{IO_2} from a low-flow device is determined.
9. Describe the basic operation of oxygen-conserving devices.
10. Define high-flow oxygen therapy and list the specifications for each device.
11. Explain the operation and uses of reservoir delivery devices.
12. Describe the operation and uses of helium/oxygen therapy.
13. Describe the operation and uses of nitric oxide.
14. Describe the operation and uses of carbon dioxide/oxygen therapy.
15. Describe the basic function of an oxygen concentrator.

KEY TERMS

air-entrainment mask
air/oxygen blender
Bourdon gauge
carbogen
flowmeter
flow restrictor
heliox
high flow
high-flow nasal cannula (HFNC)
low flow
nasal cannula
nitric oxide
nonrebreathing mask
oxygen concentrator
oxygen-conserving device (OCD)
oxygen tent
reducing valve
reservoir cannula
simple mask
Thorpe tube
transtracheal oxygen catheter

Introduction

When Joseph Priestly discovered "dephlogisticated air" (later renamed oxygen) in 1774, he unknowingly introduced two problems into the practice of medicine. The first was when to use this purified air therapeutically, and the second was how to deliver it to the patient. Oxygen therapy has particular significance for the profession of respiratory care because the first respiratory care practitioners were typically hospital orderlies who specialized in the application of oxygen.[1] From those days in the 1940s, when oxygen technicians mostly set up oxygen tents and moved large gas cylinders, a profession began to form. Currently, although the general indications for oxygen therapy are well established, there is still ongoing debate as to the best methods for safely delivering medical gases.

This chapter is primarily concerned with the equipment necessary to provide precise doses of oxygen to patients. This equipment includes the devices (i.e., **flowmeters** and regulators) that allow precise flows from bulk oxygen sources (e.g., cylinders and wall outlets) and the specific interfaces that are attached to the patient (e.g., nasal cannulas and nonrebreathing masks). The chapter will also explore other therapeutic gases, such as helium/oxygen mixtures (heliox), nitric oxide, and carbon dioxide/oxygen mixtures (carbogen).

Pressure-Regulating Devices

Once the decision has been made to administer a prescribed amount of oxygen to a patient, the next logical step is to determine the best way to do it. Typically, the patient care setting will determine what oxygen source is available. Hospitals use large bulk liquid oxygen reservoirs and complex piping systems connected to outlets at the patient's bedside. Oxygen concentrators, portable liquid oxygen units, and high-pressure tanks are commonly used to provide oxygen to patients cared for at home or in long-term care facilities. Once the oxygen source has been identified, the clinician must determine whether there is a need to obtain equipment to regulate the flow from the oxygen source and then select the appropriate patient interface.

Reducing Valves/Regulators

When full, the typical high-pressure metal alloy cylinder stores its gas at a pressure of at least 2000 pounds per square inch (psi) or pounds per square inch gauge (psig). Because this pressure is so high, it must be reduced to a considerably lower pressure. Most oxygen delivery devices and flowmeters are designed to operate at a working pressure of 50 psig (the standard pressure in hospital medical gas delivery systems). Thus, for the cylinder to be clinically useful, it must have a valve that will lower and maintain the pressure at the necessary level. Essentially, *regulator* and *reducing valve* refer to the same type of device, with the principal difference being that a regulator combines a reducing valve with some type of flowmeter (usually, a Bourdon gauge; see later in this chapter).

A **reducing valve** can be either preset by the manufacturer (fixed) or adjustable. Fixed reducing valves are set to reduce the pressure to a single level (usually, 50 psig). On the other hand, an adjustable regulator can reduce the pressure to levels selected by the operator. Adjustable regulators are uncommon because the great majority of oxygen delivery devices and pneumatic-powered equipment is designed to operate at 50 psig.

Reducing valves can be either single stage or multistage. As the names suggest, a single-stage reducing valve drops the pressure to its working level in one stage, whereas a multistage reducing valve drops the pressure in two or more stages, with each stage connected in series. Multistage reducing valves are relatively uncommon in clinical practice because they are more expensive than single-stage valves and provide a level of precision that is generally unnecessary in typical clinical applications.

As can be seen in **Figure 2-1**, a single-stage reducing valve contains the following components: inlet port, pressure gauge, high-pressure chamber, pressure-relief valve, outlet port, flexible diaphragm, ambient pressure chamber, spring, and valve stem. Once the valve on the cylinder is opened, gas enters through the inlet port into the high-pressure chamber. The pressure exerted by the gas pushes against the flexible diaphragm, which would cause the valve stem to seal the valve inlet were it not for the pressure being countered by the tension of the spring. As long as the outlet is open, the

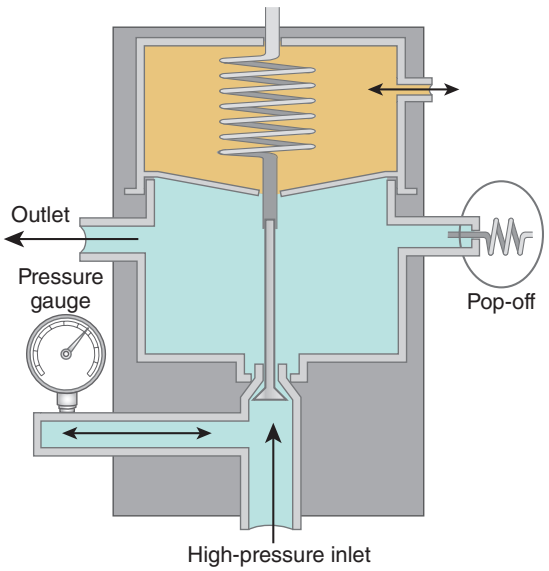

FIGURE 2-1 Single-stage regulator.

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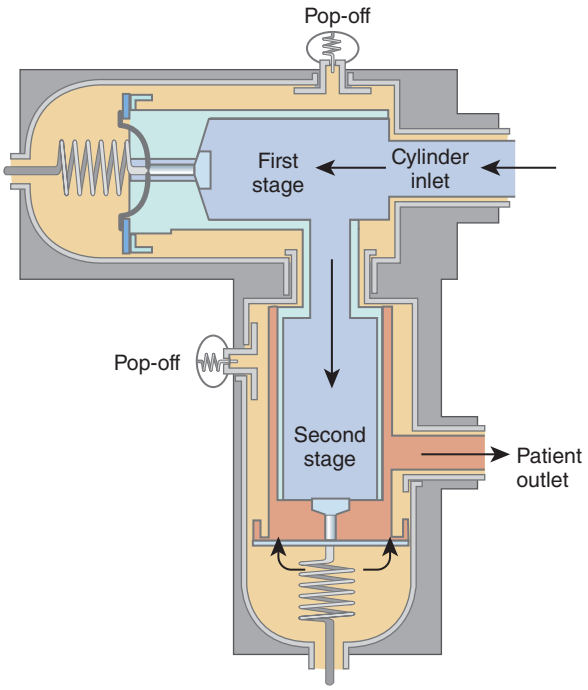

FIGURE 2-2 Multistage regulator.

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FIGURE 2-3 Thorpe tube flowmeter.

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two pressures will equilibrate and remain at the preset level. Thus, the pressure is reduced to whatever tension the spring is set for (usually, 50 psig). The pressure gauge provides a visual indicator of the contents of the cylinder.

A multistage reducing valve reduces pressure by connecting two or more single-stage regulators in a series. This type of regulator is also larger and much heavier than a single-stage regulator. In a multistage regulator, the first stage reduces pressure to a preset intermediate pressure (500–700 psig), after which, each of the following stages further reduces the pressure until it reaches 50 psig. The more regulators connected in series, the more precisely the pressure is controlled. For example, in a two-stage reducing valve, the working pressure is lowered to 200 psig in the first stage and then to 50 psig in the second stage (**Figure 2-2**). In a valve with more stages, the pressure within the cylinder is reduced more gradually. Therefore, multistage regulators provide smoother flow and more precise control of pressure when compared to single-stage regulators.

Flow-Regulating Devices

For oxygen delivery devices to accomplish their intended purpose, they generally require a well-regulated flow of gas. This is achieved through one of three types of devices: flow restrictor, Thorpe tube, or Bourdon gauge. Each device will provide a precise and measurable flow to an attached delivery device (e.g., nasal cannula or simple mask).

Thorpe Tube

The flowmeter most typically found in hospitals and other clinical venues is the **Thorpe tube** (**Figure 2-3**). The Thorpe tube is a true flowmeter in the sense that it "meters," or measures, gas flow. The device can be either pressure compensated or pressure uncompensated (**Figure 2-4**). If the flowmeter is pressure uncompensated, its accuracy is affected by changes in backpressure caused by downstream flow resistance. Also, as can be seen in Figure 2-4, the needle valve controlling the intake of gas is proximal to the tube. Virtually all Thorpe tube flowmeters produced at this time are pressure compensated. They are calibrated to produce an accurate flow rate at 50 psig.

The Thorpe tube is clear and tapered with the diameter increasing from the bottom to the top. Inside this tube is a float (usually, a steel ball). When the flowmeter is turned on, the force of the flowing gas pushes against the float, causing it to rise in opposition to gravity. As the float rises higher in the tube, the flow increases around it because the diameter of the tube is larger. Flow is indicated by the position of the float against the calibrated markings on the outside of the tube. The calibration is specific for both the type of gas (e.g., oxygen, air, or helium) and the pressure at which the gas is assumed to flow.

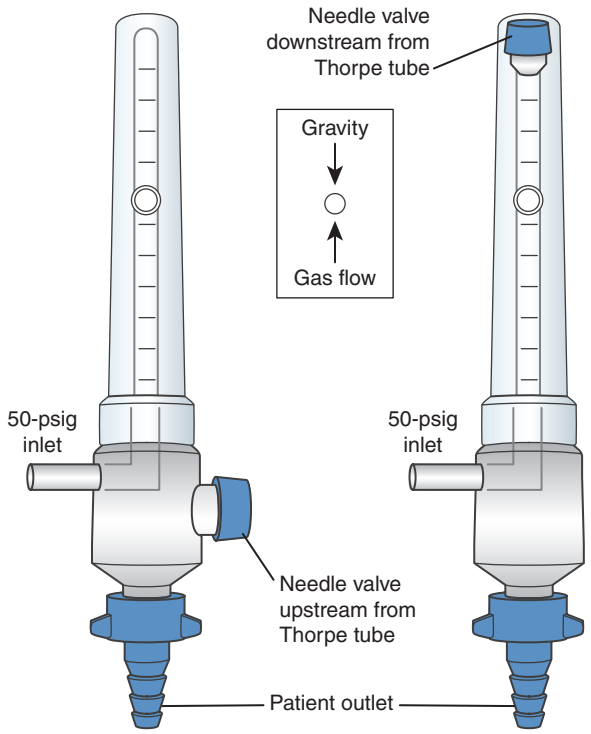

FIGURE 2-4 Thorpe tube designs: Uncompensated (left) and compensated (right).

Modified from Cairo JM, Pilbeam SP. Mosby's respiratory care equipment, 6th edition. St Louis, MO: Mosby; 1999. Reprinted with permission.

A Thorpe tube is designed to be pressure compensated by placing the needle valve downstream from the float (Figure 2-4). With this arrangement, the gas moving the float is at the supply pressure (e.g., 50 psig), so its density remains constant regardless of any backpressure after the needle valve (such as what may be produced by supply tubing kinks or large-volume nebulizers). The float on a pressure-compensated Thorpe tube will jump when the flowmeter is connected to a 50-psig pressure source. One occasionally encounters uncompensated Thorpe tubes, often called "rotameters," which are used for calibrating laboratory equipment. They are uncompensated because the needle valve is located upstream from the float. The tube is calibrated with the assumption that the float is at essentially barometric pressure. Hence, any backpressure will change the density of the gas flowing around the float and invalidate the flow scale, making the reading less than the actual flow.

The typical Thorpe tube has a flow range of 1 to 15 L/min. Some Thorpe tubes are calibrated to flows as low as 0.025 L/min for neonatal use. The flowmeter will also produce flows much greater than 15 L/min when the dial is turned as far as it will go (called the "flush" setting, perhaps as much as 40–60 L/min).

The principal disadvantage of the Thorpe tube is that it is very sensitive to gravity; it must remain vertically straight to operate properly.

FIGURE 2-5 Single-stage adjustable pressure regulator with two Bourdon gauges. The gauge on the right, the one closer to the connection to the gas source, is calibrated in either psi or psig (depending on the manufacturer), indicating the contents of the cylinder. The Bourdon gauge on the left, the one closer to the outlet containing a small-diameter fixed orifice, is calibrated in liters per minute. Flow is adjusted by turning the regulator knob, which sets the pressure, causing flow through the orifice.

Courtesy of Western Enterprises, a Scott Fetzer Company.

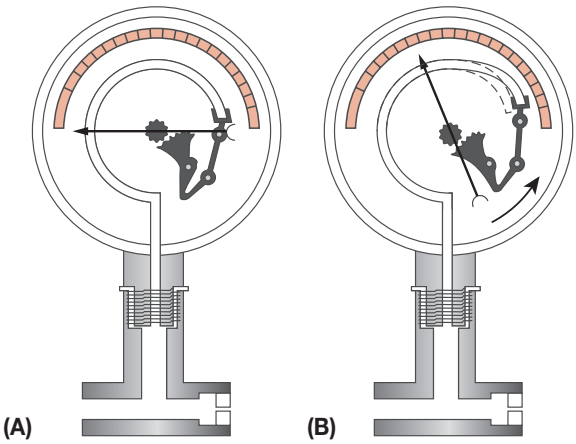

FIGURE 2-6 Bourdon gauge flowmeter. **A.** Unpressurized state. **B.** Pressurized state, causing straightening of the tube and movement of the indicator needle.

Modified from Ward JJ. Equipment for mixed gas and oxygen therapy. In: Barnes TA, editor. Core textbook of respiratory care practice, 2nd edition. St Louis, MO: Mosby; 1994.

Bourdon Gauge

The **Bourdon gauge** is a pressure gauge that is often configured as a flow-metering device (**Figure 2-5**). In terms of function, it is generally described as a fixed-orifice, variable-pressure flowmeter device.

The Bourdon gauge flowmeter contains a precision orifice; a connector; and a curved, hollow, closed tube, which changes shape when exposed to pressure (**Figure 2-6**). Although the needle on the indicator is responding to pressure changes, the scale is calibrated to read flow (usually, liters per minute). Turning the dial on the regulator adjusts the pressure in the reducing valve, which changes the pressure gradient between the valve and the fixed orifice. Changes in

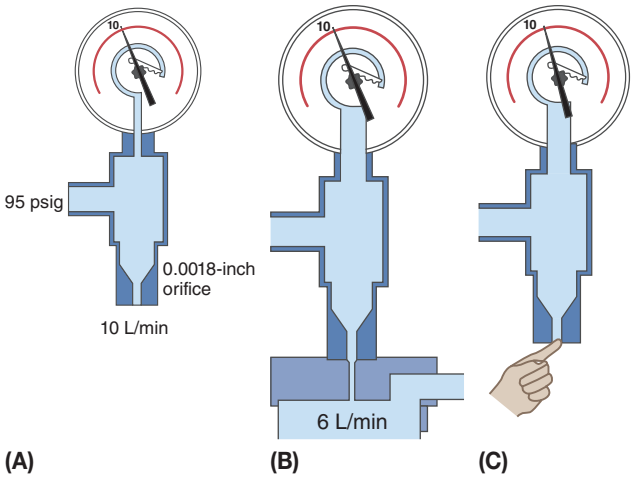

FIGURE 2-7 Bourdon gauge. **A.** The gauge displays a predictable outlet flow, assuming a constant known inlet pressure and known orifice size. **B.** Adding downstream resistance (e.g., attaching a large-volume nebulizer) causes flow to decrease, but the reading may not be changed or may increase. **C.** Even with a complete obstruction, the Bourdon gauge indicates flow because it measures pressure, not flow.

the pressure gradient cause changes in flow because the output flow is directly proportional to the driving pressure.

This relationship will hold as long as there are no restrictions distal to the orifice. However, if any restrictions do occur (such as a kink in the supply tubing), the increase in backpressure will cause the indicator to read a flow that is higher than what is actually coming out of the device. In fact, even if the outlet is completely occluded, the indicator will still register or indicate a flow (**Figure 2-7**).

Flow Restrictors

Flow restrictors are very simple flow-metering devices. As can be seen in **Figure 2-8**, the device is basically a tube with a fixed orifice placed distally to the oxygen source. It is calibrated to deliver a specific flow at a specific pressure (usually, 50 psig).

Flow restrictors are generally available in flows ranging from 0.5 to 3 L/min. There are also flow restrictors that allow the user to vary the orifice size, thus rendering the device capable of producing a variety of flows.

Advantages of flow restrictors include low cost, reliability, gravity independence, and flow specificity. Their disadvantage is that they are not backpressure compensated. Downstream resistance makes flow less than expected because the meter is calibrated with the assumption that the only resistance is the internal orifice. Flow restrictors are relatively uncommon in clinical practice, generally giving way to Bourdon gauges and Thorpe tubes.

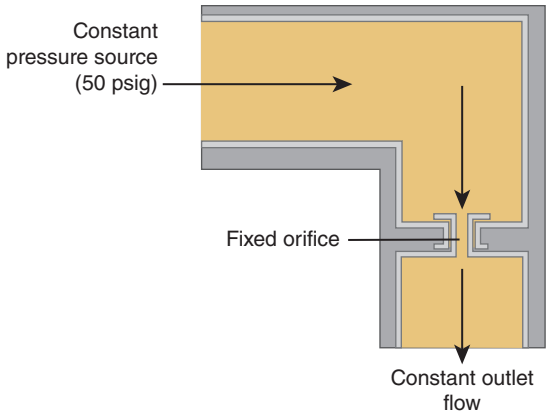

FIGURE 2-8 Schematic of a fixed-orifice flow restrictor. Flow through the orifice is proportional to the pressure difference across it.

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Air/Oxygen Blenders

Some clinical applications of oxygen therapy require that air and oxygen be combined in precise amounts to create a stable F_{IO_2}. The simplest way to accomplish this would be to combine the flow from an air flowmeter with the flow from an oxygen flowmeter. The ratio of the two flows creates the F_{IO_2}. For example, if a provider ordered a patient to receive 60% oxygen, the respiratory therapist would set each flowmeter so that the ratio of air to oxygen would be equal (e.g., set the air flowmeter at 10 L/min and the oxygen flowmeter at 10 L/min). This ratio is derived from a simple mass-balance equation:

$$\text{Mass oxygen in total flow} = \text{Mass oxygen in oxygen flow} + \text{Mass oxygen in airflow,}$$

which can be expressed as:

$$F_{TO_2} \times \text{Total flow} = 1.0 \times \text{Oxygen flow} + 0.21 \times \text{Airflow,}$$

where F_{TO_2} is the fraction of oxygen in the total flow and *total flow* is the sum of the air and oxygen flows. From this basic equation, we can derive the equation for estimating the ratio of oxygen and airflow for a desired F_{IO_2}:

$$\text{Airflow:Oxygen flow} = (1.0 - 0.21)/(F_{IO_2} - 0.21)$$

Table 2-1 gives some approximate air to oxygen ratios for various desired F_{IO_2} values.

Although combining the flows as described may be the simplest method of creating a stable F_{IO_2}, the number of possible applications this method can serve is limited. Thus, occasionally, it may be desirable to use a dedicated **air/oxygen blender**, also referred to as a proportioner.

As can be seen in **Figure 2-9**, the air/oxygen blender is connected to a high-pressure (usually, 50 psig) air source and a high-pressure oxygen source. The two

TABLE 2-1
Air:Oxygen Flow Ratios for Desired Values of Inspired Oxygen

Desired F_{IO_2}	Mix Ratio Air to Oxygen
0.24	25:1
0.28	10:1
0.3	8:1
0.35	5:1
0.4	3:1
0.45	2.3:1
0.5	1.7:1
0.55	1.3:1
0.6	1:1
0.65	0.8:1
0.7	0.6:1
0.75	0.5:1
0.8	0.3:1

Reproduced from Branson RD. Gas delivery systems: regulators, flowmeters, and therapy devices. In: Branson RD, Hess DR, Chatburn RL, editors. Respiratory care equipment, 2nd edition. Philadelphia, PA: Lippincott Williams and Wilkins; 1999.

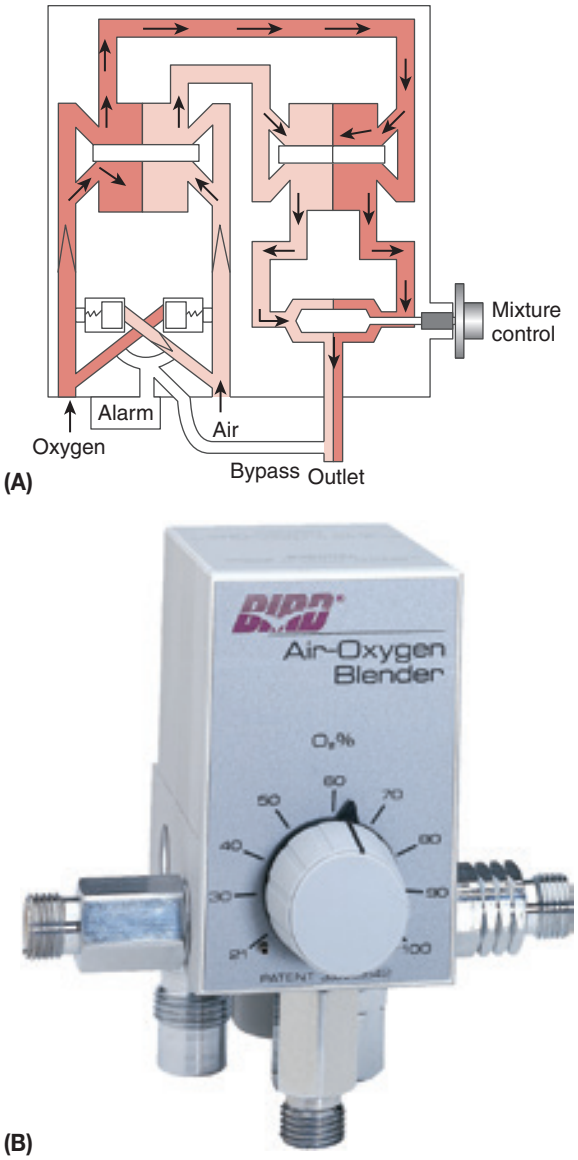


FIGURE 2-9 **A.** Schematic of an air/oxygen blender. **B.** An oxygen blender.

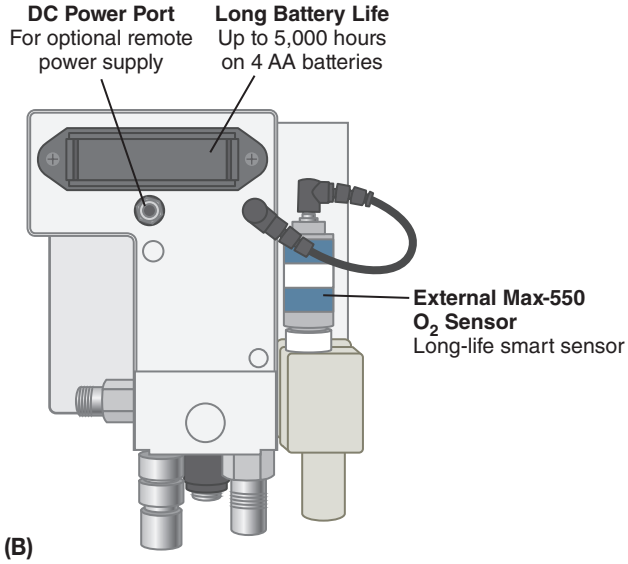
A. Modified from Ward JJ. Equipment for mixed gas and oxygen therapy. In: Barnes TA, editor. Core textbook of respiratory care practice, 2nd edition. St Louis, MO: Mosby; 1994:365-439. **B.** Reproduced with permission from CareFusion.

pressures must be equal for the device to be accurate. When activated, both air and oxygen flow into the blender and then through dual-pressure regulators, which cause the pressure of the two gases to equalize. The gases then move to a precision proportioning valve. At this point, because the pressure of the two gases is equal, the concentration of oxygen (F_{IO_2}) is controlled by varying the size of the air and oxygen inlets. The blended gas then flows out of the outlet port to the delivery device, with a small amount of the gas being shunted to an alarm.

The alarm on the blender functions to provide an audible warning whenever the pressure of one of the source gases drops below a certain specified level. Should such a failure occur, the alarm system has a built-in bypass feature that will cause the blender to switch to the remaining source gas (e.g., should the pressure of compressed air drop, the blender will switch to provide 100% oxygen).

Two key factors need to be considered whenever an air/oxygen blender is in use. The first is that the blender may not be entirely accurate. Thus, the F_{IO_2} of the output of the device should be confirmed with an oxygen analyzer. An oxygen analyzer may be added to the oxygen delivery system to verify the concentration of oxygen delivered to the patient. Blenders with oxygen analyzers incorporated into the blended gas system are commercially available. These devices provide continuous digital display of the F_{IO_2} of the output of the device. **Figure 2-10** provides an illustration of a blender with a continuous digital display of the F_{IO_2} of the output of the device. The second factor relates to the use of the blender in a closed system (e.g., continuous positive airway pressure [CPAP]). Such a system should have flow capabilities that meet or exceed the patient's inspiratory flow demands and a backup inspiratory valve in place in case of gas-flow failure. Figure 2-10 illustrates a blender with a wide range of flow rates. The ability to deliver a higher flow of gas is needed for high-flow CPAP delivery.

(A)



(B)

FIGURE 2-10 **A.** The MaxBlend 2 Blender, Maxtec Inc., has a flowmeter and oxygen analyzer incorporated into the blender. **B.** A schematic of the MaxBlend 2 Blender, Maxtec Inc., highlighting the device's features.
Courtesy of Maxtec.

Oxygen Concentrators

Outside of the acute hospital setting, oxygen therapy is commonly provided by a variety of systems, including liquid oxygen vessels, compressed gas cylinders, and **oxygen concentrators**. In North America, it is estimated that oxygen concentrators represent more than 95% of all stationary home oxygen therapy delivery systems. Around the world, oxygen concentrators represent a critical tool for the provision of oxygen therapy and are particularly important in many developing countries, where oxygen concentrators have been identified as the most consistent and lowest cost source of oxygen available.[2,3]

Oxygen concentrators are used in both medical and industrial applications and have been available commercially in some parts of the world for medical applications for over 30 years. Modern stationary oxygen concentrators are electromechanical devices that generally operate from an AC power source, weigh approximately 30 to 50 pounds, and have sound pressure levels of 39 to 55 decibels. (Specifications vary by manufacturer, make, and model.)

Oxygen concentrators separate the oxygen in the air from the other gases using a chemical sieve gas-separation technology. The most common method of separating the gases employed in oxygen concentrators is known as pressure swing adsorption (PSA). Oxygen PSA systems pump air under specific pressure through a molecular sieve bed, normally composed of a ceramic zeolite, which preferentially adsorbs the nitrogen molecules in the air while allowing the oxygen molecules to pass through the bed. At the end of the first pressurization cycle, the sieve bed is left saturated with the adsorbed nitrogen and must be regenerated before the next adsorption cycle. During the sieve bed regeneration phase, a lower pressure and a small volume of oxygen are routed to the saturated bed to help "wash" the nitrogen off the sieve molecules in a depressurization process, referred to as desorption. This cyclic "swinging" of pressures from higher (adsorption) to lower (desorption) is what gives the PSA process its name. Most oxygen concentrators operate using a two-bed system, with one bed adsorbing nitrogen while the other bed is desorbing. Because the sieve beds adsorb only nitrogen, a small amount of argon passes through with the oxygen. As a result of the presence of argon, the maximum output purity of modern oxygen concentrators is about 96%. Once separated, the output oxygen is typically collected in a small storage (product) tank, pressurized, and delivered at the prescribed setting to the user.

There are various types, makes, and models of stationary oxygen concentrators commercially available (**Figure 2-11**); the most common models can deliver a range of continuous flows up to 5 L/min, with an oxygen purity of greater than or equal to 87%, although many modern devices routinely exceed 93%. Owing to advancements in sieve material efficiency and compressor technologies, there are now a number of commercially available medical concentrators capable of providing a continuous flow of oxygen up to 10 L/min. Continuous-flow devices supply oxygen at a fixed rate, generally measured in liters per minute. As a patient

FIGURE 2-11 Stationary oxygen concentrators.

FIGURE 2-12 Portable oxygen concentrators.

breathes using a continuous-flow device, they simply draw in oxygen from the available fixed flow of gas. The flowmeters used with oxygen concentrators are similar in specifications and performance and operate in the same way as those commonly used in institutional healthcare settings.

In recent years, a new class of smaller, lightweight (some under 5 pounds) oxygen concentrators have been introduced to the market. This new category of oxygen concentrators, commonly referred to as portable oxygen concentrators (POCs), also operate using the PSA system (**Figure 2-12**). This group of devices is classified by the oxygen delivery methodology: (1) conserving (pulse dose) only or (2) continuous flow and pulse dose. The latter devices may deliver up to 3 L/min of continuous flow and can vary greatly in the available pulse-dose range (setting) and output volumes. Unlike continuous-flow systems, pulse-dose devices deliver oxygen in response to the patient's inspiratory demand (see the section Oxygen-Conserving Systems later in this chapter).

Technical characteristics common to all oxygen concentrators for home medical use include low operating pressures, small volumes of oxygen stored and delivered under low pressures, and no significant alteration of the surrounding ambient gas mixture or oxygen concentration. Contrary to common misperceptions, oxygen concentrators do not produce large volumes of oxygen; do not store such gases at high pressures; and do not vent high levels of oxygen into the ambient atmosphere, which are all characteristics that make them ideal and safe for home use. Oxygen pressures within the concentrator system are typically <25 psig, and the output delivery pressures are often quite low, with an operating range of about 5–8 psig. The safety and efficacy profile of oxygen concentrators is well documented, as is evidenced by the approval from the Federal Aviation Administration (FAA) of POC use on commercial aircraft. In contrast, other traditional home oxygen systems, such as stationary liquid vessels or compressed gas cylinders, can store large volumes of oxygen at very high pressures (2000–3000 psi) with output delivery pressures of 20 to 50 psi.

Oxygen concentrators are the current standard of care for the provision of low-flow oxygen in the home and other nonhospital settings. They are designed for laypersons to operate; are relatively easy to use, safe, and quiet; and, generally, require little maintenance and servicing. Modern oxygen concentrators have been demonstrated to be quite reliable and cost effective.

Oxygen Delivery Devices

Oxygen therapy is very commonly applied in both acute care and long-term care. The principal indications for oxygen therapy are hypoxemia and cardiopulmonary distress. The principal goal of oxygen therapy is to treat or prevent hypoxemia and minimize the effects of hypoxemia.[4]

For medical gas therapy to be effective therapeutically, it must be administered to the patient using some type of interface. Traditionally, these interface devices can be classified as **low flow**, **high flow**, reservoir, and enclosure. Device selection for a particular patient will depend on how much oxygen the patient needs (i.e., FIO_2), how much flow the patient needs, the patient's need for comfort and mobility, and the need for precise delivery of desired oxygen concentrations (**Table 2-2**).

Low-Flow Oxygen Delivery Devices

A low-flow oxygen delivery device provides a portion of the total flow of gas a patient inhales per breath. These devices are also referred to as variable-performance devices because the actual tracheal FIO_2 can vary from breath to breath. The following situation will serve to demonstrate how these devices work (simplified):

Patient inspiratory volume (tidal volume) = 500 mL

Inspiratory time = 1 second

Oxygen flow (nasal cannula) = 2 L/min (33.3 mL/second)

In this situation, the patient is receiving 33.3 mL of 100% oxygen per breath. The remainder of the inspiratory volume (500 mL − 33.3 mL = 466.7 mL) comes from room air (21% oxygen). Some textbooks give

TABLE 2-2
Comparison of Interfaces Used for Oxygen Therapy

F_{IO_2} Characteristics	Performance Characteristics/F_{IO_2} Stability	
	Fixed	Variable
Low <0.35	Air-entrainment mask Mask attached to an air-entrainment nebulizer Isolette Oxygen hood	Nasal cannula Nasal catheter Transtracheal oxygen catheter
Moderate 0.35–0.60	Air-entrainment mask Mask attached to an air-entrainment nebulizer Oxygen hood	Simple mask
High >0.60	Oxygen hood Mask attached to an air-entrainment nebulizer	Partial rebreathing mask Nonrebreathing mask

gross approximations of the F_{IO_2} delivered by low-flow systems (e.g., nasal cannulas) based on a mathematical model that takes into account the factors (breath rate and ratio of inspiratory time to expiratory time, I:E) that affect inspiratory time and the small amount of oxygen possibly stored in the anatomic reservoir (i.e., nose and upper airway) during the latter portion of exhalation when flow is zero for patients with normal lungs. Interestingly, patients with chronic obstructive pulmonary disease (COPD) often do not have a period of zero flow at the end of expiration; therefore, the anatomic reservoir may not provide any extra oxygen, and, hence, the equation overestimates the F_{IO_2}.[5]

As can be seen by the previous example, two factors go into defining a low-flow oxygen delivery system: (1) only a relatively small portion of the patient's inspiratory volume comes from the device, and (2) the patient's tracheal F_{IO_2} while wearing the device is highly variable and dependent on such factors as tidal volume, respiratory rate, and inspiratory time. In clinical practice, the variability of the F_{IO_2} is critical for the clinician to understand. As will be seen later in this chapter, there are guidelines for equating oxygen liter flows with specific F_{IO_2}s (e.g., 2 L/min = 28%). However, these flows are *only rough approximations*.

In actual practice, the patient's tracheal F_{IO_2} could possibly vary from one breath to the next, especially if the patient's respiratory pattern is relatively unstable. As a general rule, the tracheal F_{IO_2} will vary as the inspiratory volume varies, such that there is an inverse correlation between tidal volume and F_{IO_2} (i.e., the higher the tidal volume, the lower the F_{IO_2}, and vice versa).

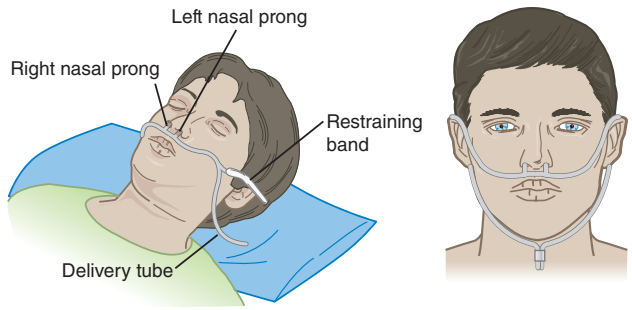
The most common low-flow device in use today is the nasal cannula. (The high-flow nasal cannula will be addressed in the section High-Flow Devices later in the chapter.) Patients requiring continuous oxygen in the home may use a **reservoir cannula**, which has been designed to conserve oxygen (e.g., pendant or mustache). The transtracheal catheter is a low-flow device used most commonly for long-term oxygen therapy. The nasal catheter is a low-flow device that is rarely used clinically.

Nasal Cannula

The **nasal cannula** is by far the most common type of oxygen delivery device in use today. It generally consists of at least 7 feet of small-bore oxygen delivery tubing connected to two short prongs that are inserted into the nose with the prongs angled down (**Figure 2-13**). There are cannulas manufactured for home and long-term care use that provide 25 feet of small-bore tubing before the connection to the two prongs. The longer supply tubing enables patients to ambulate and remain connected to a stationary oxygen source, such as oxygen concentrators.

Obviously, for the cannula to be an effective delivery device, the nares and nasal passages must be patent. Although the cannula may be worn for extensive periods of time, the prongs and continuous flow of gas may irritate the inner lining of the nose or cause skin irritation or breakdown around the ears, face, and/or opening of the nares. Gauze or foam pads can be used to protect areas where the plastic cannula may rub the skin. Padding pressure points, such as behind the ears or over the cheekbones, may be especially helpful to prevent skin breakdown. The prongs of the nasal cannula should occlude more than 50% of the nares. Tightly fitting prongs may cause breakdown around or within the nares.

Because this is a low-flow device, it does not provide the total flow needed to meet all of the inspiratory demands of the patient and should not be used on patients for whom a precise F_{IO_2} is necessary. For adults, the standard flow range is 1 to 6 L/min. Although some sources cite the maximum flow as 8 L/min, this flow is not common in actual practice, primarily because there is very little F_{IO_2} gain with flow rates above 6 L/min. Additionally, flows greater than 6 L/min may irritate the nasal mucosa, causing patient discomfort.



(A) (B)

(C)

FIGURE 2-13 **A.** Nasal cannula with elastic strap. **B.** Over-the-ear–style nasal cannula. **C.** Various styles of nasal prongs.
C. Courtesy of Teleflex.

The standard F_{IO_2} range is 0.24 to 0.40 at these flow rates. However, recent studies have shown a significant degree of variability in correlating flow to tracheal or pharyngeal F_{IO_2}.[6-9] A very general rule for determining F_{IO_2} at a specific flow rate is the "rule of fours," which states that the F_{IO_2} will change 4% for every liter per minute above 1 (e.g., 1 L/min ≈ 24%, 2 L/min ≈ 28%, etc.). This is only a crude approximation; actual tracheal F_{IO_2} is subject to the variables indicated previously for low-flow oxygen delivery systems. Owing to the variability of the F_{IO_2}, it is generally recommended that the clinician titrate the flow of this low-flow device to an objective measure of the patient's oxygenation status. Pulse oximetry is often used to noninvasively monitor a patient's oxygenation status. An example of a common physician order: *Oxygen at 2 L/min by nasal cannula. Titrate oxygen flow to maintain an S_pO_2 of 93% to 95%.*

For pediatric and neonatal patients, the flow range for a standard nasal cannula is much lower owing to the patients' anatomical features and lower tidal volume. Two liters per minute is considered the maximum flow rate for a nasal cannula used for infants.[10] The flow rate appropriate for infant ranges from 0.25 to 2 L/min.[11] The maximum flow for pediatric patients is 3 L/min.

In the past, it was common practice to attach the nasal cannula to a bubble humidifier. However, studies showed that this practice does not provide benefit

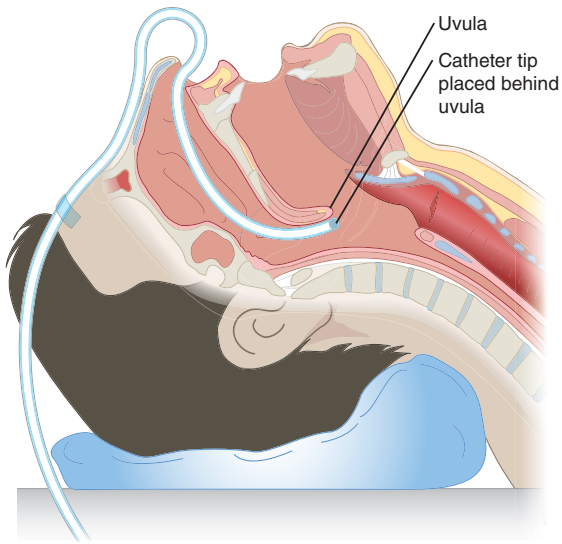


FIGURE 2-14 Nasal catheter for oxygen administration.

to the patient. Based on this research, clinical practice guidelines suggest using a bubble humidifier with flow rates that are greater than or equal to 4 L/min or if the patient complains of nasal dryness.[6]

Nasal Catheter

The nasal catheter is a long, narrow tube with a series of holes on the distal end; the approximate outside diameter is usually between 3 and 4 mm. It is generally made of soft, flexible plastic. This device is inserted through the nose to a level just above and behind the uvula (**Figure 2-14**). The proximal end is connected to oxygen delivery tubing. The catheter should be lubricated with a water-soluble gel just before insertion. Insertion itself should be slow and careful, with the catheter being advanced along the floor of the nasal passage. The catheter should be secured with tape after it is inserted. Generally, the catheter is withdrawn and inserted into the other nare approximately every 8 hours.

Historically, the nasal catheter was used as an oxygen delivery device similar to the way the nasal cannula is used today. Although the nasal catheter is still commercially available, it is rarely used in day-to-day clinical practice because the nasal cannula is equally efficacious, more comfortable, and easier to use. The flow range for the nasal catheter is 1 to 6 L/min. The F_{IO_2} range is about the same as that for the nasal cannula, 24% to 44%. As with the nasal cannula, the tracheal F_{IO_2} is highly variable and dependent on the patient's respiratory rate and tidal volume.

The use of the nasal catheter may be problematic. First, at least one nare and nasal passage must be entirely patent. Second, the presence of the catheter within the nose is irritating and may cause inflammation and bleeding. There is also a chance that mucus can clog the small holes at the distal end, reducing the flow

of gas through the device. Additionally, tape used to secure the catheter may irritate the facial skin.

Transtracheal Catheter

The **transtracheal oxygen catheter** is a flexible, small-diameter tube (about 3.3 mm), generally made of soft plastic or Teflon. It is inserted directly into the trachea through a small incision through the tracheal wall, usually between the second and third rings. When properly positioned, the tip of the catheter is 2 to 4 cm above the carina (**Figure 2-15**). It is then secured with a bead chain necklace. Once inserted, it is removed only for cleaning or replacement.

The transtracheal catheter was first described in 1982 and became commercially available in 1986, at which time it was inserted by the modified Seldinger technique. It is meant as a replacement for the nasal cannula for patients who are on long-term oxygen therapy. In 1996, Lipkin's surgical approach was introduced as an alternative. Regardless of the insertion technique, the process is composed of four clinically defined phases:[12] (1) patient selection and evaluation, (2) tract creation, (3) beginning of therapy in an immature tract (removal of the catheter requires a guide wire), and (4) regular therapy through a mature tract.

The principal advantages of the transtracheal catheter are that it provides an alternative for patients who do not tolerate a nasal cannula, provides relief to patients experiencing nasal irritation and bleeding with nasal cannula use, and is easy to conceal under clothing—an advantage for those oxygen-dependent patients who are self-conscious about wearing their oxygen device in public.

FIGURE 2-15 Transtracheal oxygen catheter in place.
Courtesy of TransTracheal Systems.

Because the catheter is placed directly in the trachea, thus bypassing the upper airway, the patient generally requires less oxygen flow to produce like effects. Christopher[12] estimates that oxygen flow can be reduced by over 50% at rest and about 30% during exercise.

However, there are limitations to its use. A surgical procedure is necessary to initially place the catheter. Because the catheter resides in the trachea, there is risk for tracheal irritation and/or infection. Mucus may clog the distal end, reducing or completely obstructing the flow of oxygen to the patient. Therefore, patients must remove the catheter and clean it on a regular basis.

The flow range for the transtracheal catheter is 0.25 to 4 L/min, producing an FIO_2 range of 0.22 to 0.35.

Reservoir Delivery Devices

Reservoir delivery devices allow the continuous flow of oxygen from the source to accumulate within that interface and thus to increase the amount of oxygen available to the patient just before each inhalation. Reservoir devices are generally made of plastic and can be masks (simple mask, partial rebreathing mask, or nonrebreathing mask) or cannulas (mustache or pendant).

Simple Mask

The **simple mask** is a single unit that fits over the mouth and the bridge of the nose. An adjustable elastic strap, attached to the periphery of the mask, wraps around the back of the patient's head, securing it in place. A flexible, thin metal strip molds the mask to the contours of the bridge of the nose, preventing gas from escaping and irritating the patient's eyes. There are small holes on either side of the mask that serve as outlet ports for exhaled gas. Long, small-diameter tubing connects the mask to the oxygen source (**Figure 2-16**). The inside of the mask has a reservoir of approximately 100 to 200 mL. Although the FIO_2 from the device is highly variable, the reservoir helps to increase the FIO_2 potential.

Because the FIO_2 is variable and not much higher than that for the nasal cannula (maximum of approximately 0.50 within the accepted flow range of the mask), the use of the simple mask is essentially limited to those clinical situations in which a nasal cannula is unavailable (e.g., in an emergency oxygen kit) or when the use of a nasal cannula is contraindicated (e.g., skin breakdown around or within the nares). It may also be useful in patients who need a moderate amount of oxygen over a short period of time because its design makes it easier to place on a patient's face than a nasal cannula. It is not recommended for patients who require a precise concentration of oxygen.[4]

There are limitations to the use of the simple mask. The reservoir could collect carbon dioxide exhaled at the end of a breath. If the flow of oxygen to the mask is not sufficient to flush out this carbon dioxide, the patient could then rebreathe the carbon dioxide on the next

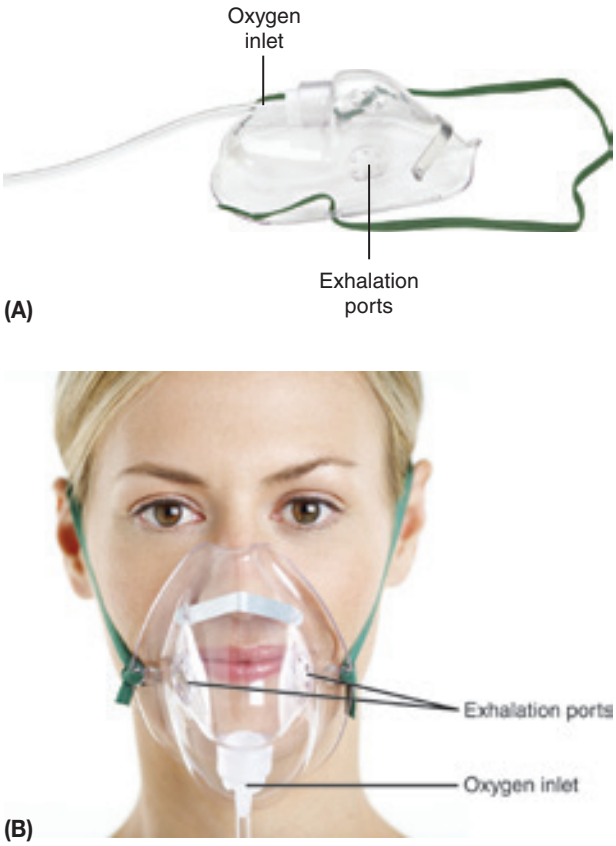


FIGURE 2-16 **A.** Schematic of a simple oxygen mask. **B.** Oxygen mask in place on a patient.

A. Courtesy of Teleflex Incorporated. © 2020 Teleflex Incorporated; **B.** © Corbis/age footstock.

inhalation. For this reason, it is important for the clinician to ensure the flow of oxygen to the mask is at least 5 L/min. Precautions should be taken to avoid or quickly detect any interruptions in the flow of oxygen to the device (i.e., disconnections).[6,11] Long-term use of the mask can potentially result in skin irritation and breakdown; interfere with communication by muffling speech; and limit the patient's ability to eat, drink, and expectorate.

The generally acceptable flow range for the simple mask is 5 to 10 L/min. The F_{IO_2} range is approximately 0.35 to 0.50. Again, remember that the F_{IO_2} is variable, largely determined by the patient's respiratory rate and tidal volume.

Partial Rebreathing Mask

The partial rebreathing mask is a tight-fitting face mask usually made of disposable plastic. It has small holes on both sides that serve as exit ports for exhaled gas. The primary feature of the mask is a reservoir bag attached to the bottom (**Figure 2-17**). Seven feet of small-bore

FIGURE 2-17 Schematic of a partial rebreathing oxygen mask.

Modified from Scanlan CL, Wilkins RL, Stoller JK. Egan's fundamentals of respiratory care, 7th edition. St Louis, MO: Mosby; 1999.

tubing connects the oxygen flowmeter to a port just above the reservoir bag.

The name *partial rebreathing mask* is derived from the fact that a portion of the patient's exhaled gas (generally, the first third) flows into the reservoir bag and is then subsequently rebreathed during the next inhalation. The original idea behind the creation of this mask was to conserve oxygen in situations where the supply of oxygen was limited (e.g., using a high-pressure oxygen tank). Because the first third of the patient's exhaled gas comes from the anatomic dead space, the assumption is that the patient will not rebreathe carbon dioxide. Therefore, this type of mask may not be the interface of choice in clinical situations where it is desirable for the patient to rebreathe carbon dioxide (e.g., hyperventilation syndrome).

Generally, the partial rebreathing mask is used when a patient requires a moderate F_{IO_2} (e.g., 0.50–0.60) for a short period of time. Because this mask may not provide the total flow needed by the patient, it is unable to guarantee precise F_{IO_2} delivery.

Similar to a simple mask, a partial rebreathing mask is relatively easy to assemble and apply. Once the flow of oxygen to the device has filled the reservoir bag, the mask can be applied to the patient's face and secured with an adjustable elastic strap. The oxygen flow is then adjusted so the bag does not deflate to more than one-half of its volume during inspiration. Failure to provide adequate flow will result in the delivery of lower oxygen concentrations to the patient. When operated properly, this device delivers moderate to high concentrations of oxygen.

As with any mask, the partial rebreathing mask restricts the patient's access to atmospheric gas. The same precautions taken with a simple mask apply with this device as well. The clinician must ensure that the minimum oxygen flow is adequate (at least 5 L/min) to prevent rebreathing of carbon dioxide and that any disruptions to the flow of oxygen to the device are prevented or readily detected.

As with any face mask, the patient's ability to eat, drink, or expectorate is severely limited. Because the mask must fit snuggly against the skin of the patient's face, there is potential risk for skin irritation and breakdown. It is important to note the integrity of the skin before the application of the mask. The skin should then be assessed at scheduled intervals. Any redness, irritation, or breakdown should be noted and communicated to the physician.

The generally accepted flow range for the partial rebreathing mask is 8 to 15 L/min. This results in an F_{IO_2} range of about 0.40 to 0.70. It should be remembered that, like the low-flow devices described previously, the F_{IO_2} is variable and will be partially influenced by the patient's respiratory rate and tidal volume.

Nonrebreathing Mask

The **nonrebreathing mask** has the same basic design as the partial rebreathing mask with the addition of three one-way valves (usually, circular flaps made of soft rubber). Two of the valves cover the holes on both sides of the mask. These valves are designed to open to the atmosphere when the patient exhales and close when the patient inhales, thus reducing access to room air. The third valve is between the reservoir bag and the mask. This valve is designed to open when the patient inhales and close when the patient exhales to prevent the patient's exhaled gas from entering the reservoir (**Figure 2-18**). The design minimizes any dilution of oxygen with room air or the patient's exhaled breath, so the nonrebreathing mask can provide high concentrations of oxygen.

The nonrebreathing mask is most useful for patients who have high oxygen requirements for relatively short periods of time. These patients might include those with acute heart failure, trauma, carbon monoxide poisoning, and transient severe hypoxemic failure.

Similar to the partial rebreathing mask, it is important to have oxygen flowing to the mask and filling the reservoir before fitting it to the patient's face. The adjustable elastic band secures the mask in place. A snug fit restricts the air entrainment, thus maintaining a high F_{IO_2}. Once the mask is in place, the oxygen flow is adjusted to ensure that the reservoir does not fully collapse during inspiration. Generally, this requires minimum flows of 10 to 15 L/min.[4,9]

The limitations and precautions for this mask are identical to those of the partial rebreathing mask. However, if the flow of oxygen were to stop, the risk of harm would be greater with the nonrebreathing mask. The presence of the one-way valves covering the side ports on the sides of the mask interferes with the patient's ability to entrain room air. Although it is less common, some manufacturers produce nonrebreathing masks with one-way valves covering both side ports. If you remove one of the valves, the risk of harm is reduced if flow is interrupted.

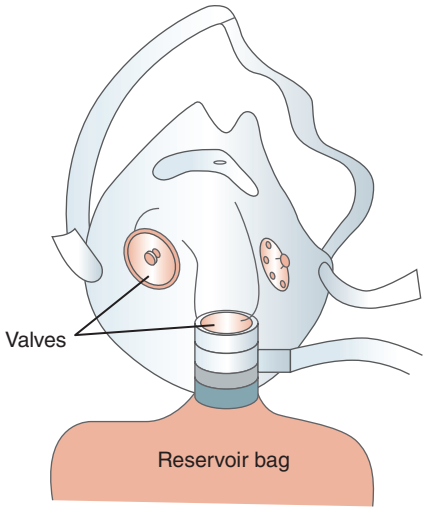


FIGURE 2-18 **A.** Schematic of a nonrebreathing mask. **B.** Nonrebreathing mask in use on a patient.

A. Modified from Scanlan CL, Wilkins RL, Stoller JK. Egan's fundamentals of respiratory care, 7th edition. St Louis, MO: Mosby; 1999. **B.** © Andrew Gentry/Shutterstock.

The generally reported flow range for the nonrebreathing mask is 10 to 15 L/min; however, depending on the patient's inspiratory effort, flows greater than 15 L/min may be necessary to keep the reservoir bag partially inflated during inspiration. Theoretically, the concentration of oxygen should approach 100%; however, published reports indicate an F_{IO_2} range of 0.60 to 0.80.[2,7] The actual F_{IO_2} is variable and dependent on the seal of the mask, the oxygen flow, and the patient's respiratory rate and tidal volume.

Oxygen-Conserving Systems

The term **oxygen-conserving device (OCD)** has been used to describe a variety of oxygen technologies that are intended to increase the duration of use of a portable low-flow oxygen system by limiting or conserving the flow of oxygen to only the inspiratory portion of the breathing cycle. OCDs are also referred to in the scientific literature as intermittent flow devices (IFDs), demand oxygen delivery devices (DODDs), and

pulsed-dose oxygen conservers (PDOCs). In this text, we will use OCD to represent the broad category of conserving devices.

OCDs intended for use in the management of patients receiving long-term oxygen therapy (LTOT) were first introduced commercially in the early 1980s. Reservoir nasal cannula systems were introduced around 1983, and mechanical oxygen-conserving devices followed in 1984.[13] Although OCD technology has been around for more than 35 years, widespread acceptance and the dramatic rise in use have been observed in the United States over only the past 15 to 20 years. Today, nearly every modern portable oxygen device incorporates some form of oxygen-conserving technology. OCDs are routinely used with ambulatory LTOT patients to a level that is arguably the standard of care in the United States.

Pulsed-Dose Oxygen-Conserving Devices

Pulsed-dose oxygen-conserving devices (PDOCs) are a logical technological extension of continuous, low-flow oxygen delivery devices. Although low-flow oxygen therapy prescriptions are typically written in liters per minute, these devices actually deliver an unpredictable volume of oxygen to the patient. For example, a patient prescribed 2 L/min of oxygen by nasal cannula does not actually inspire 2 full liters of oxygen; the 2 liters of gas flowing per minute is available to draw from only during inspiration; the rest is wasted during expiration. PDOCs were designed to conserve oxygen by delivering pulses of gas only during inspiration, thus avoiding the waste typically seen with a nasal cannula.

Modern PDOCs are either electronically or pneumatically operated devices and typically deliver oxygen on demand (**Figure 2-19**). The patient's demand is sensed as the pressure drops caused by inspiratory flow past the sensor (by a nasal cannula). Once triggered, the device delivers a predetermined flow of gas over a preset time interval, which produces a certain dose, or bolus, of oxygen. The clinical foundation of PDOCs relies on the assumption that the oxygen participating in gas exchange in the lungs enters the airways quickly, during the first two-thirds of the inspiratory cycle. Oxygen flowing at the end of the inspiration, during exhalation and the pause before the next inspiration, is essentially wasted because it plays no role in gas exchange and blood oxygenation. The physiology of breathing suggests that approximately one-third of a person's inspiratory volume remains in the larger airways, sinuses, nose, and mouth (anatomical dead space). Gas held in the anatomical dead space does not participate in alveolar gas exchange and represents the first volume of exhaled gas. Early work by Tiep and Lewis noted that the efficiency of pulsed oxygen therapy can be improved by focusing the oxygen delivery on early inspiration.[14]

FIGURE 2-19 Examples of commercially available pulsed-dose oxygen-conserving devices that fit on E cylinders of oxygen. Pneumatically controlled device (top). Electronically controlled device (bottom).

In the United States and in many other countries, PDOCs are currently accepted as a standard of practice for stable, ambulatory LTOT users. PDOC technology is incorporated into nearly all modern ambulatory oxygen systems, including small cylinders, lightweight liquid oxygen vessels, and portable oxygen concentrators. There are a few key elements associated with efficient PDOC technology, including bolus size, trigger sensitivity, and bolus flow/speed. A common assumption with PDOCs is that the earlier the oxygen bolus is delivered into the inspiratory cycle, the more efficient the oxygen delivery will be, which correlates to F_{IO_2}. To respond and deliver oxygen effectively in this relatively small window of time requires excellent trigger sensitivity and a very quick bolus response. Oxygen boluses delivered late in inspiration may not produce the desired F_{IO_2} and therefore will be less effective in improving blood oxygen levels because portions of the bolus may fall into the anatomical dead space.

OCDs operate using precision valves and orifices to sense breathing by measuring extremely small pressure changes in the tubing and then responding (triggering) rapidly to deliver the oxygen. The valve systems may be pneumatic, electronic, or a combination of systems. The outlet pressures, flow rates, and patterns are precise and

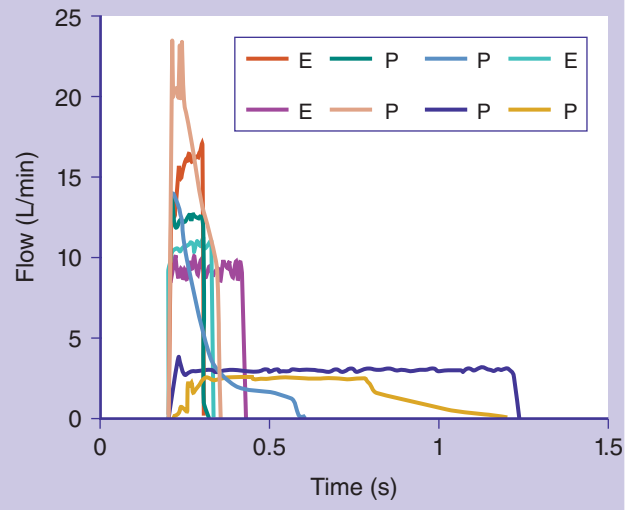


FIGURE 2-20 Oxygen pulse flow waveforms for PDOCs. Electronically controlled (E) and pneumatically controlled (P).

calculated to deliver a specific volume of oxygen. The trigger sensitivity, flow rate, bolus size, and waveform characteristics per setting are generally specific to each make/model of OCD and are not uniform across all devices (**Figure 2-20**). That is to say, the setting of 1, 2, 3, and so on for a given device may deliver a different net amount of oxygen per breath than another make/model of OCD at the same setting. This is a very important point that is often confusing to clinicians and a frequent source of debate among engineers, researchers, healthcare practitioners, and patients.

PDOCs are low-flow oxygen delivery devices that are modeled after continuous low-flow nasal cannula oxygen therapy. In theory, they are designed to deliver a volume of oxygen consistent with what would be delivered using a traditional continuous-flow nasal cannula system (i.e., settings of 1, 2, etc., are often claimed in the operator's manuals to be equivalent to 1 L/min, 2 L/min, etc., of continuous flow). However, continuous-flow oxygen delivery by nasal cannula results in high breath-to-breath F_{IO_2} variability. Therefore, the setting number on a PDOC is based on simplifying assumptions, including typical values for physiologic variables that include tidal volume, respiratory rate, I:E ratio, inspiratory flow rate, and anatomic dead space. However, these values rarely match the actual parameters of a real patient at any moment during oxygen therapy. This suggests that proper and ideal use of a PDOC requires some type of titration procedure (e.g., pulse oximetry) to determine the setting(s) on a particular device that satisfies the patient's oxygenation needs during various activities of daily living.

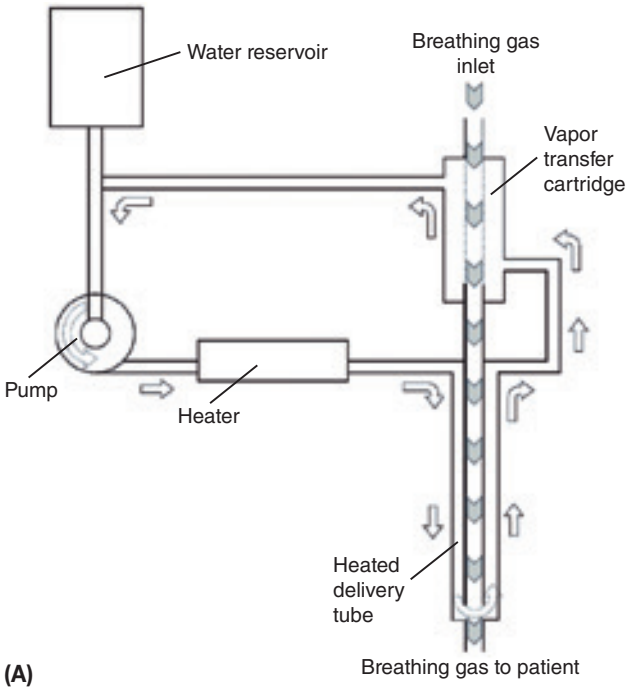
High-Flow Devices

A high-flow device is generally defined as one that can deliver a precise F_{IO_2} at a flow rate that meets or exceeds the patient's inspiratory demand. Such devices are also classified as fixed-performance oxygen delivery systems. The three main types of high-flow delivery devices are **high-flow nasal cannulas (HFNCs)**, **air-entrainment masks**, and air-entrainment (large-volume) nebulizers.

High-Flow Nasal Cannula

The generally accepted upper limit for the nasal cannula is 6 L/min in adults. One of the primary reasons for setting this upper limit is that flows greater than 6 L/min are cool and dry the nasal mucosa, thus causing irritation and patient discomfort. High-flow nasal cannulas offer humidified air/oxygen mixtures at high flows (up to 60 L/min) warmed to body temperature. In recent years, these oxygen delivery devices have gained popularity owing to their ability to enhance patient comfort and tolerance, compared with traditional high-flow oxygenation systems, such as nasal masks and nonrebreathing systems. HFNC systems are less apt than traditional oxygenation systems to permit entrainment of room air during patient inspiration because gas mixtures are delivered at flow rates that meet or exceed the patient's inspiratory needs and expired air is flushed from the upper airway during expiration, therefore assuring a more reliable delivery of prescribed F_{IO_2}. The flushing of upper airway dead space also improves ventilatory efficiency and reduces the work of breathing.[15] HFNCs also generate a positive end-expiratory pressure (PEEP), which may counterbalance auto-PEEP, further reducing ventilator work; improve oxygenation; and provide backpressure to enhance airway patency during expiration, which permits more complete emptying. HFNCs have been tried for multiple indications, including secretion retention, hypoxemic respiratory failure, and cardiogenic pulmonary edema, to counterbalance auto-PEEP in patients with COPD and as prophylactic therapy or treatment of respiratory distress following surgery and extubation.[15]

There are several devices commercially available that deliver heated high-flow oxygen through a nasal cannula. The Precision Flow, from Vapotherm (**Figure 2-21A**), incorporates an internal electronic blender and flow controller to deliver heated, humidified high-flow gas therapy. Water and gas pathways are incorporated into a disposable high- or low-flow patient circuit. Circuits are also available for administration of specialty gas, such as heliox and nitric oxide. Because the blender and flow controller are electronic, an internal battery is incorporated into the unit for emergency backup in the event of an AC power failure. The battery life is limited to 15 minutes and requires 2 hours to recharge. A transfer unit is also commercially available, which offers a manifold to connect to E-sized oxygen and air cylinders and medical-grade battery power. Battery power can last up to 60 minutes when the Precision Flow transfer unit is used. The Precision Flow Plus provides the

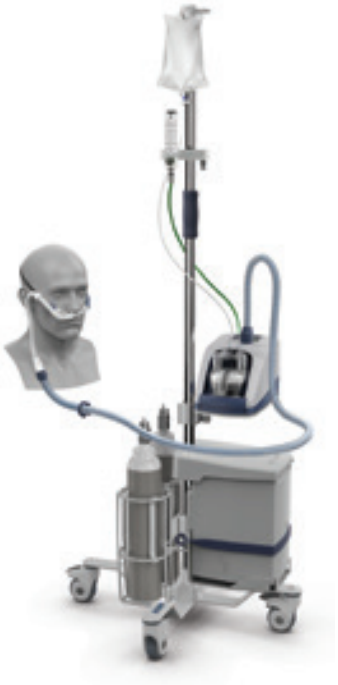


(A)

(B)

(C)

FIGURE 2-21 Examples of a device that can deliver heated high-flow gas mixtures through a nasal cannula. **A.** Schematic of Vapotherm; **B.** Precision Flow, Vapotherm; **C.** Precision Flow Heliox, Vapotherm.



(D)

(E)

FIGURE 2-21 (*Continued*) **D.** AIRVO 2, Fisher & Paykel Healthcare. **E.** MaxVenturi, Maxtec.
A–C. Courtesy of Vapotherm. **D.** Courtesy of Fisher & Paykel Healthcare.

aforementioned heated high-flow nasal cannula features along with RS-232 bidirectional communication, which allows the device to interface with an electronic medical record. Stereo audio jacks are also available, which integrate the device to the nurse call system. Special cartridges allow for the delivery of nitric oxide at lower (up to 8 L/min) and higher (up to 60 L/min) flows. A special unit, the Heliox Precision Flow, connects to an 80:20 helium and oxygen compressed gas source and provides heated high-flow heliox therapy through a nasal cannula. Flows of 1 to 40 L/min can be delivered through this device (**Figure 2-21B**).

Salter Labs produces a nonheated high-flow system consisting of a special nasal cannula (1600HF) and bubble humidifier (#7900). This system is designed to provide flows of up to 15 L/min. It is capable of delivering oxygen concentrations of up to 75% and a relative humidity of up to 79%.[6,16]

The AIRVO 2, from Fisher & Paykel Healthcare (**Figure 2-21C**), is an electrically powered flow generator designed to deliver heated high-flow oxygen gas mixtures at 2 to 60 L/min through a specially designed nasal cannula. A heated passover humidifier, with an autofill water chamber connection, is incorporated into the system to provide active humidification. Temperature, flow, and oxygen concentration can be adjusted with this device. Because the device is electrically powered, it can connect to air and oxygen cylinders, wall outlets, or an oxygen concentrator and air compressor.

The MaxVenturi, from Maxtec, is a device that uses the Venturi principle to mix ambient air and oxygen and deliver the mixtures at flow rates up to 60 L/min (**Figure 2-21D**). This device has a galvanic fuel cell analyzer incorporated into the system for continuous FIO_2 monitoring. The MaxVenturi will connect to a heated humidification system and interface to deliver high-flow oxygen therapy.

FIGURE 2-22 Examples of interfaces used for heated high-flow nasal oxygen. The cannula prongs are larger compared to a standard nasal cannula.
Courtesy of Fisher & Paykel Healthcare.

The specific interface used for high-flow oxygen therapy is a special nasal cannula that comes in various sizes, depending on the age of the patient (**Figure 2-22**).

Several studies have shown that the high-flow nasal cannula is a viable alternative to reservoir masks for patients requiring high concentrations of oxygen.[17-19] In a systematic review, Kernick and Magarey[20] reported the high-flow nasal cannula has clinical utility and can effectively improve oxygenation in adult critical care patients.

Published reports address the debate regarding the potential for a high-flow nasal cannula to produce a CPAP effect and serve as a viable alternative to nasal or mask CPAP. In a systematic review of nine studies in preterm infants, Dani et al.[21] concluded that the high-flow nasal cannula should be limited to patients requiring oxygen therapy. Parke et al.,[22] using the Fisher-Paykel Optiflow system, examined the amount of positive pressure generated in the airways of post–cardiac surgery patients. The Fisher-Paykel Optiflow system is capable of delivering oxygen concentrations from 21% to 100% and flow rates up to 50 L/min. Pressures of about 3 cm H_2O were generated at a flow of 50 L/min. The investigators concluded that the pressure generated by the high-flow nasal cannula was of questionable clinical significance.

In a bench study of pressures generated in an infant model, Volsko et al.,[23] using flow rates of 2 to 6 L/min, determined that the high flows did not generate clinically important continuous airway pressure. Urbano et al.[24] studied the amount of positive pressure generated at various flows in a pediatric model. They also concluded that the high flows produced a low-level CPAP.

Based on the previous data, high-flow nasal oxygen systems should be considered oxygen delivery systems, not nasal CPAP systems. High-flow oxygen systems appear to be a viable alternative to reservoir masks in patients requiring moderate concentrations of oxygen. Roca et al.[19] compared the high-flow nasal cannula with oxygen administration by face mask in patients experiencing acute respiratory failure and concluded that the high-flow nasal cannula was well tolerated and associated with improved oxygenation. The use of high-flow oxygen for preoxygenation during rapid sequence intubation is gaining favor. In a randomized controlled trial of 40 critically ill subjects with hypoxemic respiratory failure, Simon et al. compared the effect of preoxygenation by bag-valve mask and high-flow nasal cannula on oxygen saturation during intubation.[25] The mean lowest S_pO_2 during intubation was comparable between the high-flow nasal cannula and the bag-valve mask ventilation groups.[15] The mean lowest S_pO_2 during intubation was 89 ± 18% in the high-flow nasal cannula group and 86 ± 11% in the bag-valve mask ventilation group ($P = 0.56$).[15] In a literature review of nasal cannula apneic oxygenation during intubation, focusing on two components, oxygen saturation during intubation and oxygen desaturation time, Gleason et al. identified 14 studies that supported the benefits of using a nasal cannula during emergency intubation to minimize hypoxemia during rapid sequence intubation in subjects with respiratory failure.[26]

Gas heated to body temperature at 95% to 100% relative humidity may have the added benefit of increasing ciliary activity and decreasing the viscosity of airway secretions. Regardless of its intended use, because it is delivered directly into the nose, rather than over the face, high-flow oxygen therapy is generally viewed as more comfortable and less confining for the patient than a mask. Oxygen is delivered in a manner that does not disrupt the patient's ability to communicate, eat, drink, or expectorate.

The prongs of the high-flow nasal cannula are a wider bore than those of the traditional low-flow nasal cannula. The prongs are placed inside the patient's nares, and the cannula unit is secured to the patient's face by an adjustable elastic band. Stiff, smooth lumen tubing at the end of the cannula connects to the special high-flow humidifier.

Therapeutic benefits are improved when the patient's nares and nasal passages are patent. The larger-bore prongs may be uncomfortable for some patients. Skin integrity must be assessed, and any irritation or breakdown addressed. As a precaution, the temperature of the humidified gas flow is monitored to reduce the risk of thermal injury. There is also a potential for gastric distension because a relatively high flow of gas is administered intranasally. As a further precaution, because of the increased heat and humidity, microbial contamination can be a risk.

Air-Entrainment Masks

The air-entrainment mask is a high-flow oxygen delivery device that can provide a variety of precise F_{IO_2}s at flows that can greatly exceed the patient's inspiratory demand. Although these masks are often referred to erroneously as Venturi masks, they operate on the principle of jet mixing, not the Venturi principle.[27] A 7-foot hose connects the oxygen flowmeter to a jet that is placed just below the reservoir of the mask. Small holes (or entrainment ports) surround the jet (**Figure 2-23**). As the oxygen flows through the jet, it accelerates. Fast-moving oxygen molecules collide with the stationary molecules in the room air and drag them through the ports. The mixture of room air and oxygen then flows to the patient.

The specific F_{IO_2} is determined by the ratio of room air to oxygen in the gas mixture (every F_{IO_2} between 0.22 and 0.99 has a unique ratio; see later in this section). The ratio of room air to oxygen is controlled by varying the diameter of either the jet or the entrainment ports, depending on the manufacturer. Generally, the smaller the diameter of the jet, the more room air will be entrained, thus resulting in a decreased F_{IO_2}. Conversely, the smaller the entrainment ports, the less room air will be entrained, thus resulting in an increased

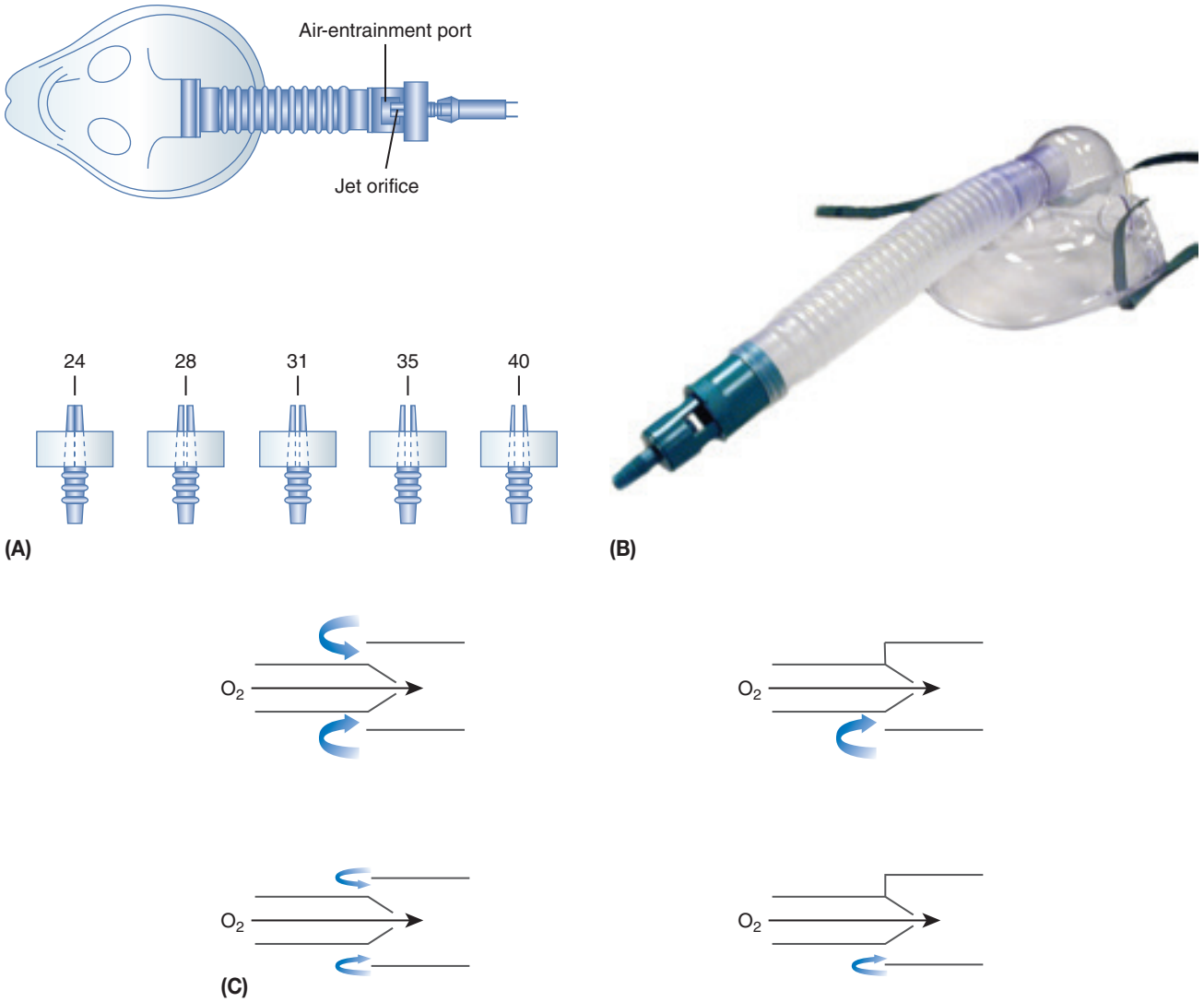


FIGURE 2-23 **A.** Schematic of air-entrainment oxygen mask with different sized jet ports for delivering different oxygen concentrations. **B.** Entrainment mask. **C.** Changes in oxygen concentration can also be achieved by changing the size of the air-entrainment ports. The less entrainment of room air, the higher the oxygen concentration delivered by the mask. F_{IO_2} is lowest in upper left diagram (most air entrainment) and highest in lower right diagram (least air entrainment).

A. Adapted from Kacmarek RM. Methods of oxygen delivery in the hospital. Prob Respir Care 1990;3:536-574. **B.** Courtesy of Dr. Dean Hess.

F_{IO_2}. Studies have shown that these masks are reasonably accurate, especially at an F_{IO_2} of 0.30 or less and in patients with relatively low inspiratory demand (<200 L/min).[28-31]

Some air-entrainment masks include an optional collar that goes around the entrainment ports. A large-diameter hose connects the collar to a large-volume nebulizer. This provides additional humidification, should that be desired.

Air-entrainment masks are mostly used in patients who require precise concentrations of oxygen in the low to moderate range (e.g., patients with COPD who chronically retain carbon dioxide) or in patients who have a highly variable respiratory pattern. They might also be useful for conditions requiring low concentrations of oxygen in which a nasal cannula may not be well tolerated (e.g., cleft palate and nasal septal defects).

Air-entrainment masks are confining and may interfere with a patient's ability to communicate, eat, drink, or expectorate. Especially while eating, the patient may frequently remove the mask, disrupting the oxygen therapy. In such cases, a nasal cannula may be used to provide oxygen therapy for short durations (e.g., during meals). The clinician should take care that the entrainment ports remain free of obstruction.

Traditionally, air-entrainment masks provide six to seven F_{IO_2} settings, ranging from 0.24 to 0.50 (e.g., 0.24, 0.28, 0.31, 0.35, 0.40, and 0.50). The oxygen flow should be set so that the combined flow of air and oxygen always exceeds the patient's inspiratory demand. Woolner and Larkin[30] recommend that the total flow exceed 30% of the patient's peak inspiratory flow at settings of 0.30 or less. Other sources recommend that the total flow should be at least 3 times the patient's minute

volume. Mask manufacturers traditionally publish recommended flowmeter settings for each F_{IO_2}. These settings range from 4 L/min for 0.24 to 12 to 15 L/min for 0.50.

The OxyMask, from Southmedic Inc., Canada, is an oxygen mask that has several large holes along the periphery (**Figure 2-24**). This mask incorporates a mushroom-shaped pin diffuser, seated approximately 2 cm from the nose and mouth, to concentrate and direct oxygen toward the mouth and nose (**Figure 2-25**). Flow is adjustable from 1.5 to 15 L/min and can deliver oxygen concentrations from 24% to 90%. A randomized, single-blind, crossover study compared the OxyMask with the Venturi mask in 13 oxygen-dependent subjects with chronic, stable respiratory disease.[32] Compared to the Venturi mask, the OxyMask provided a higher P_{O_2} at a lower flow rate, without evidence of carbon dioxide retention.[32]

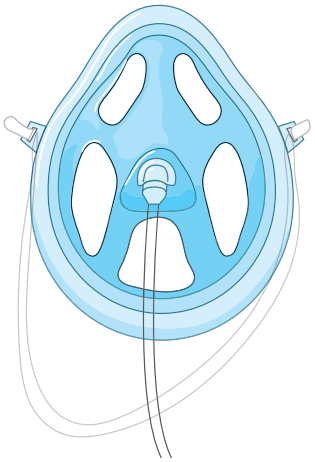


FIGURE 2-24 An illustration of the OxyMask, from Southmedic Inc., Canada.

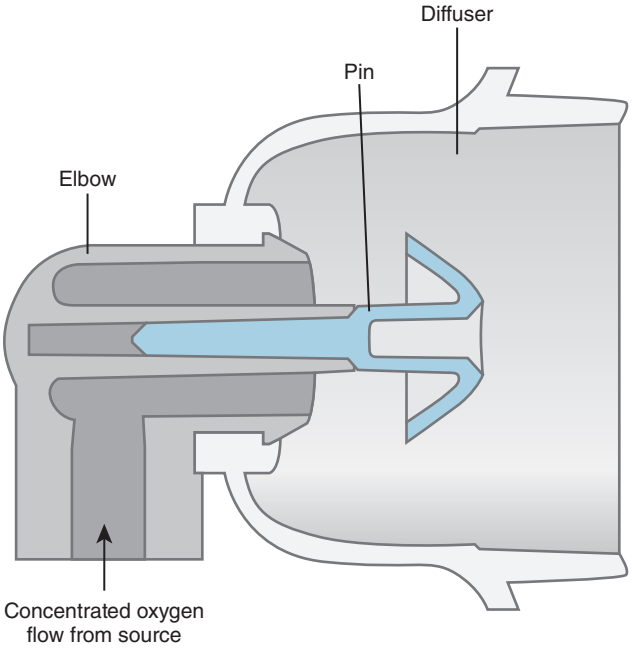


FIGURE 2-25 A cross-section schematic of the cup that houses the mushroom-shaped pin diffuser.

Air-Entrainment Nebulizer

The air-entrainment nebulizer large-volume nebulizer (**Figure 2-26**), is a device that provides both a precise F_{IO_2} and particulate water or saline (i.e., aerosol). It is used in conjunction with face masks (generally, aerosol

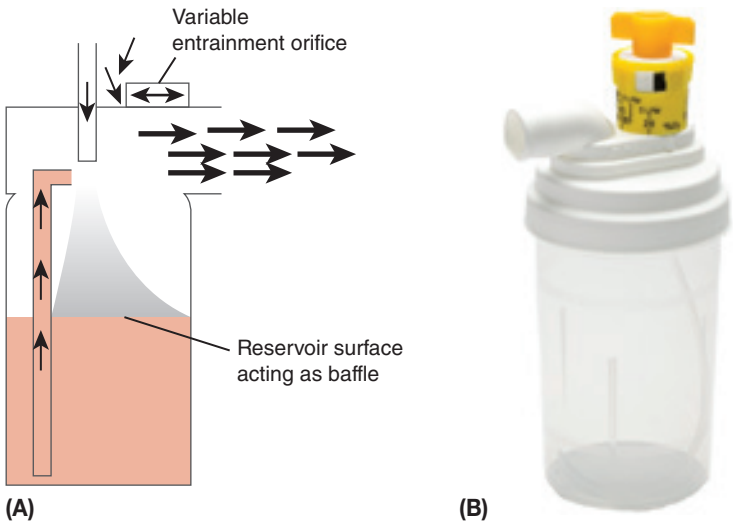


FIGURE 2-26 Air-entrainment large-volume nebulizer. **A.** Schematic of the flow through an air-entrainment large nebulizer. **B.** Photo of an air-entrainment large-volume nebulizer.

A. Modified from Cohen N, Fink J. Humidity and aerosols. In: Eubanks DH, Bone RC, editors. Principles and applications of cardiorespiratory care equipment. St Louis, MO: Mosby; 1994. **B.** Courtesy of Teleflex.

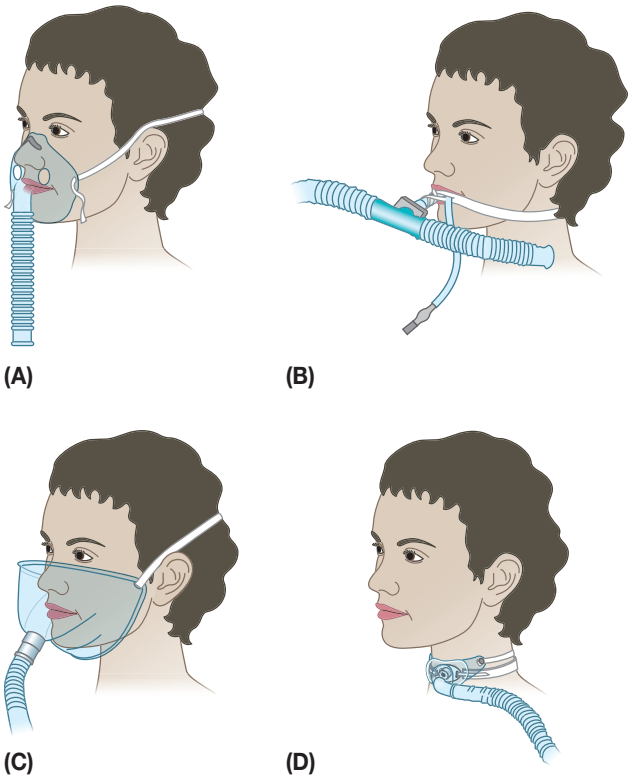


FIGURE 2-27 **A.** Aerosol mask. **B.** Briggs T-piece. **C.** Face tent. **D.** Tracheostomy collar.

Adapted from Fink JR, Hunt GE. Clinical practice of respiratory care. Philadelphia, PA: Lippincott Williams & Wilkins; 1999.

masks), face tents, tracheostomy masks, and T-pieces (Brigg's adaptors) (**Figure 2-27**). These devices work on the same principle as entrainment masks. Oxygen from a flowmeter flows through a jet nozzle surrounded by an entrainment port. The acceleration of the gas molecules through the jet causes room air to be drawn in through the port in such an amount as to produce a specific ratio of air to oxygen. The device is designed so that the diameter of the jet is fixed but the size of the entrainment port is variable, controlled by a labeled dial at the top.

Because the air-entrainment nebulizer combines high gas flow with aerosol particles, it is especially useful for patients with artificial airways (endotracheal or tracheostomy tube). A patient whose upper airway is bypassed generally requires that the inspiratory gas be heated and humidified to minimize the drying of the airway mucosa. Because some patients with tracheostomy tubes might not require supplemental oxygen, the device can be attached to a compressed air flowmeter or an air compressor and used strictly to provide humidified gas to the lower airway.

The air-entrainment nebulizer is filled with sterile water or normal saline and attached to the appropriate gas source (usually, an oxygen flowmeter). The entrainment dial is set to the prescribed F_{IO_2}, and the flowmeter is set at the appropriate liter flow (see later in this chapter). The device is connected to the appropriate patient interface (face mask, T-piece, face tent, or tracheostomy mask) by large-bore corrugated tubing.

The air-entrainment nebulizer is a high-flow device. Thus, the clinician must ensure that the total flow of gas (air plus oxygen) going to the patient always exceeds the patient's inspiratory demand. This concern for sufficient total flow is especially significant when the F_{IO_2} is 0.50 or above. Under these circumstances, it is recommended that two air-entrainment nebulizers be used in parallel to double the flow going to the patient. Based on the information presented in Foust et al.,[33] it is further recommended that these devices not be used at all for patients who require an F_{IO_2} of 0.80 or greater.

Because the device generates an aerosol, there is always the potential for microbial contamination. This is especially important to monitor because, in the case of artificial airways, the upper airway defense mechanisms have been bypassed. Also, as the aerosol particles flow through the corrugated tubing, some of the particles will rain out and accumulate in the gravity-dependent portion of the tubing. The presence of water in the tubing could potentially create backpressure, which will decrease the amount of air being entrained and thus increase the F_{IO_2}. A drainage bag should be placed in the circuit to minimize this accumulation. As a final precaution, the clinician should ensure that the fluid in the nebulizer reservoir never falls below recommended levels.

The air-entrainment nebulizers commercially available are disposable and offer six to eight F_{IO_2} settings, generally ranging from 0.28 to 1.0. The flow rates are adjusted to ensure a total flow that always exceeds inspiratory demand. Often, in actual practice, the clinician will use a flowmeter setting of 15 L/min.

Calculation of Required Flow to Meet Patient Inspiratory Demand

A high-flow device is only high flow if the total flow delivered to the patient at least meets the patient's peak inspiratory flow. The patient's peak inspiratory flow can be approximated by first assuming the flow waveform is sinusoidal and estimating the inspiratory time, based on the spontaneous breathing frequency, and the tidal volume, based on the patient's ideal body weight. Then, the air and oxygen flows necessary to meet this peak flow are calculated from the entrainment ratio:

1. *Calculate the ventilatory period:* This is equal to 60 seconds divided by the patient's breathing frequency (e.g., if the patient is breathing 20 times a minute, the ventilatory period is 3 seconds).
2. *Calculate the inspiratory time:* A sine wave has an inspiratory to expiratory time ratio of 1:1, so the inspiratory time is half the ventilatory period (e.g., 3 seconds divided by 2 = 1.5 seconds).
3. *Estimate the patient's tidal volume:* This is roughly 7 mL per kilogram of ideal body weight. Ideal body weight is estimated using one of these equations:

Male ideal body weight (kg) = 50 + [0.91 × (Height in centimeters − 152.4)]

Female ideal body weight (kg) = 45.5 + [0.91 × (Height in centimeters − 152.4)]

For example, a male with a height of 5'10" (178 cm) has an ideal body weight of about 73 kg. The estimated tidal volume is thus 7 mL/kg × 73 kg = 511 mL.

4. *Calculate the peak inspiratory flow:* Average inspiratory flow is tidal volume divided by inspiratory time (e.g., 511 mL/1.5 s = 341 mL/s). Convert milliliters per second to liters per minute using a factor of 0.06. For example, (341 mL/s) × (60 s/min) × (1 L/1000 mL) = 20 L/min. Peak inspiratory flow is calculated by using the fact that the peak value of a sine wave is 1.6 times the mean value. Rounding up for safety, we get: Peak flow = 2 × Mean flow (e.g., Peak flow = 2 × 20 L/min = 40 L/min).
5. *Determine the entrainment ratio from the desired* F_{IO_2} (see also Table 2-1): Airflow to oxygen flow = (1.0 − 0.21)/(F_{IO_2} − 0.21). For example, if we want to deliver 40% oxygen, then airflow to oxygen flow = (1.0 − 0.40)/(0.40 − 0.21) ≈ 3.
6. *Determine the oxygen flow to an entrainment mask that will make the total flow delivered to the patient at least equal to the patient's peak inspiratory flow:* The entrainment ratio gives the number of parts air per parts oxygen per minute. The total parts are the entrainment ratio plus 1. Divide the estimated peak inspiratory flow by the number of parts to get the oxygen flow setting. For example, the entrainment ratio for 40% oxygen is 3. Total parts are 3 + 1 = 4. Oxygen flow required to make a total flow equal to the estimated peak inspiratory flow = 40 L/min ÷ 4 = 10 L/min. Note that this is a conservative estimate because, if the patient really does have a sinusoidal inspiratory flow waveform, the peak flow exists for only a fraction of a second and the flow during most of the inspiration is well below this value. Therefore, providing 40 L/min of total flow to our example patient should be more than enough to meet his flow demands and assure a stable F_{IO_2}.

Note that the higher the F_{IO_2}, the lower the total flow for any given oxygen flowmeter setting. If the patient requires a high F_{IO_2} and also has a high estimated peak inspiratory flow (e.g., is breathing rapidly), the total flow can be doubled by attaching two nebulizers in tandem (**Figure 2-28**).

Enclosure Devices

As the name would suggest, these devices encompass all or part of the patient's body. Oxygen flows into the device, increasing the F_{IO_2} inside the enclosure. Currently, enclosure devices are used almost exclusively with neonates and infants. Examples of enclosures include oxygen hoods, incubators, and oxygen tents.

Oxygen Hoods

Oxygen hoods are devices that fit around the head of a neonate or infant. Oxygen then flows into the hood from a heated humidifier attached to an air/oxygen blender or from an air-entrainment nebulizer (**Figure 2-29**). The hoods are typically made of transparent plastic, which allows the clinical team to observe the neonate or infant receiving oxygen therapy within the enclosure.

The oxygen hood is used for neonates or infants who require a low to moderately high F_{IO_2} but cannot tolerate other delivery devices.[34] Although only the patient's head is within the hood, there is still the potential to

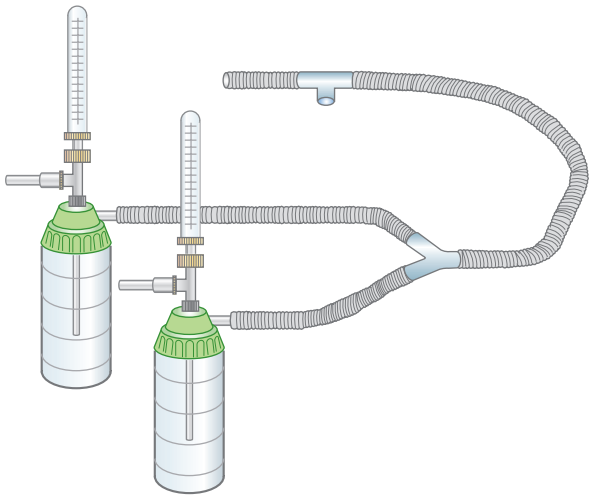


FIGURE 2-28 Total flow to the patient can be increased by joining two nebulizers.

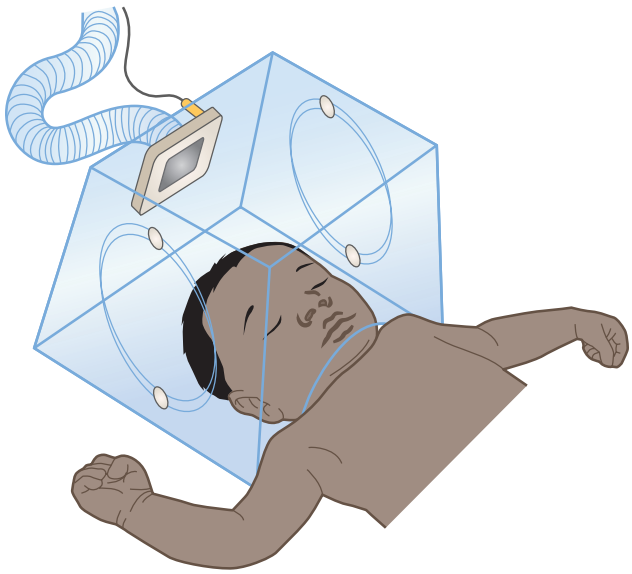


FIGURE 2-29 Oxygen hood.

disrupt therapy, such as for feeding or providing routine nursing care. In these cases, an alternative form of oxygen delivery should be available to the neonate or infant.

Because infants and neonates are particularly sensitive to temperature changes, the temperature in the hood should be such that it preserves a neutral thermal environment.[9] Thus, the oxygen going into the hood should be heated and the temperature inside the hood monitored.

The baby's blood oxygen level should be monitored to minimize the propensity for hypoxia or hyperoxia, typically by noninvasive oxygen saturation monitoring (S_pO_2). Also, oxygen concentrations may vary within the hood, so the FIO_2 should be monitored with an oxygen analyzer whose sensor is placed as near the mouth and nose as possible.[9] Another concern is the increased noise level produced by the flow of oxygen in the hood.[35] This should be considered and monitored as well. One method that has been suggested to reduce noise levels when using a heated air-entrainment nebulizer is to power the nebulizer with compressed air and bleed in the oxygen.[36]

Flow rates into the hood should be greater than 7 L/min to flush out carbon dioxide.[11,34] Generally, flows in the 10 to 15 L/min range should be sufficient for infants.[11] Because the flow is generated through either an air/oxygen blender or an air-entrainment nebulizer, the FIO_2 can theoretically range from 0.21 to 1.0. However, although patients requiring high oxygen concentrations can be managed in the oxygen hood, it is difficult to maintain an FIO_2 greater than 0.5 because of the neck opening and the need to open the hood for nursing care.[34]

Incubator

The incubator is an enclosure device designed to contain the entire body of the neonate at a temperature that will facilitate thermal stability. It is usually made of transparent plexiglass (**Figure 2-30**).

Although it can be used as an oxygen delivery device, it is most often used to provide a temperature-controlled environment to small infants and neonates. To accomplish this, temperature is regulated by a servo-controlled mechanism and a sensor attached to the patient. As with the oxygen hood, the patient should be maintained in a neutral thermal environment. Humidity can be provided by a blow-over humidifier built into the unit or by an external humidifier.

Oxygen delivery is achieved by connecting small-bore tubing from a flowmeter to a nipple connector on the unit. Some incubators have two oxygen connections, one for an FIO_2 of around 0.40 and one for high concentrations of oxygen. This is accomplished by opening or closing an air-entrainment port. Although some units have solenoids that can control the inward flow of oxygen, it is still difficult to regulate the oxygen concentration within the enclosure because the incubator is frequently opened to provide care and it has a large inside volume, making it less than ideal as an oxygen delivery device. For this reason, hoods are sometimes used inside the incubator. The internal FIO_2 should be monitored intermittently, and the patient's oxygenation status should be checked, especially if a high concentration is needed to prevent or minimize hyperoxia. At least one manufacturer, Dräger Medical, makes an incubator with automatic control of oxygen from 21% to 65%.

FIGURE 2-30 Infant incubator.

Oxygen Tent

As the name suggests, the **oxygen tent** is a clear plastic enclosure that fits over the entire bed. The patient remains within the enclosure. Oxygen flows into the device usually from an air-entrainment nebulizer or a high-output aerosol generator, producing a relatively dense mist. The mist is cooled by a refrigeration unit or by flowing over ice. The oxygen tent was one of the first oxygen delivery devices used; however, it is seldom used today, especially for oxygen delivery.

The primary use of the tent is to provide a cool, moist, oxygenated environment for patients experiencing severe laryngotracheobronchitis.[37] In this situation, the cool mist might facilitate vasoconstriction and thus help to relieve the upper airway obstruction associated with the condition. Also, it could potentially be useful in pediatric patients who are too large for an oxygen hood.

However, the value of this therapy is questionable, and informal communication among respiratory care managers (e.g., from professional organization listservs) suggests that many hospitals have eliminated tent therapy altogether.

There are many problems associated with oxygen tents. The first is the risk of electric shock. This could result from sparks generated by any electronic or friction device (e.g., call light or friction toy) contained in the enclosure. Second, it is very difficult to control F_{IO_2} within the enclosure because of the enormous volume and because the tent is frequently opened to observe the child or provide care. The F_{IO_2} should be monitored periodically with an oxygen analyzer, with the sensor placed near the patient's face.[37] A third problem is that the dense mist can make it difficult to observe the patient from outside; thus, it becomes necessary to open the enclosure often. Also, with the enclosure, there is a slight risk of asphyxiation. Finally, should the refrigeration unit fail or the flow of gas into the tent be disrupted, the cooling effect along with the oxygen would be lost.

There are no recommended flow ranges for the oxygen tent available in the peer-reviewed literature. Clearly, the flow needs to be relatively high (i.e., >10 L/min) to flush any exhaled carbon dioxide out of the large volume of the enclosure. The oxygen concentration is highly variable, regardless of the device used to generate the oxygen flow. This is again because of the large volume and the frequent opening of the tent. It is highly unlikely that F_{IO_2}s greater than 0.40 can be achieved consistently. Because of this variability, the patient's oxygenation should be monitored periodically.

Heliox

Helium is a gas that is less dense than either air or oxygen (**Table 2-3**). It is also an inert gas, meaning that it does not take part in biochemical reactions in the body. The low density is the property that makes it useful as a medical gas because it decreases the effective flow resistance in patients with upper airway obstruction (e.g., foreign body aspiration, postextubation stridor, or croup). This can be appreciated by recalling that airway obstruction causes turbulent flow when breathing air or oxygen. Turbulent flow requires a higher pressure drop across the airway for a given flow than normal laminar flow and hence increases the effort to inspire. Whether turbulence develops depends on the density of the gas; the lower the density, the less high the flow can be without turbulence (Reynolds number[38]). Thus, breathing helium decreases turbulence around an airway obstruction and decreases the work of breathing. On the other hand, for laminar flow (typical in the lower airways), the pressure drop across the airway is dependent on the viscosity of the gas (Poiseuille's law[38]); the higher the viscosity, the higher the pressure drop across the airways for a given flow and the higher the effort to inspire. Because helium has a higher viscosity than air and only slightly less viscosity than oxygen, breathing helium may have limited value for diseases affecting the small airways (e.g., emphysema and asthma). Nevertheless, there is some evidence of benefit in the management of pediatric and adult respiratory disease.[39,40]

Because helium is inert, it must be mixed with oxygen to support life. The mixture is called **heliox**. Heliox is available in standard mixtures in large compressed gas cylinders (80% oxygen/20% helium or 70% oxygen/30% helium). A heliox mixture may be diluted with oxygen to increase the F_{IO_2}, but diluting with oxygen decreases the concentration of helium. An F_{IO_2} greater than 0.40 has a low concentration of helium and probably no clinical benefit.

Nonintubated patients may receive heliox therapy using a nonrebreathing oxygen mask (**Figure 2-31**). If you use a flowmeter calibrated for oxygen to deliver heliox, the lower density of an 80% helium/20% oxygen mixture will cause the actual flow of heliox to be 1.8 times greater than the indicated flow. However, accurate flow measurement is not necessary for mask administration because the only requirement is that flow be sufficient to keep the reservoir bag from deflating on inspiration.

TABLE 2-3
Physical Properties of Medical Gases

Gas	Density (g/L)	Viscosity (μ poise)	Thermoconductivity (μ cal × cm × 5 × ° K)
Air	1.293	170.8	58.0
Oxygen	1.429	192.6	58.5
Helium	0.179	188.7	352.0

Courtesy of Dr. Dean Hess.

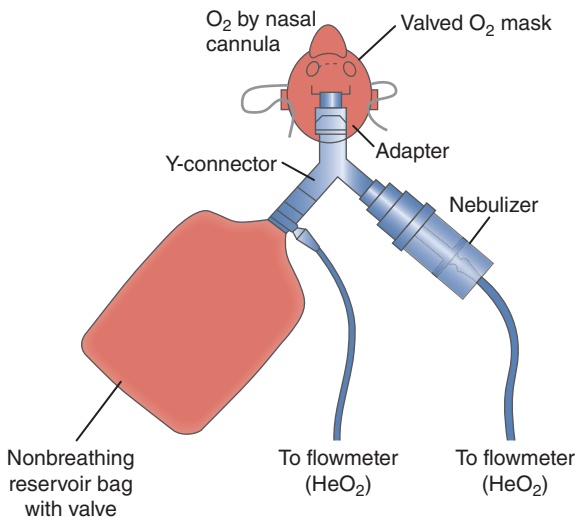


FIGURE 2-31 Mask setup for administration of heliox.

Heliox can be administered through a heated high-flow nasal cannula, as previously described. However, caution should be taken when administering this specialty gas mixture with a mechanical ventilator. Some ventilators (e.g., Avea, CareFusion, and Servo-I, from Getinge) are designed to deliver accurate ventilation with heliox. Ventilators not designed for heliox use may be adversely affected by the density, viscosity, and thermal conductivity differences of the gas compared to air or oxygen.[41]

Ventilation with helium/oxygen in place of air/oxygen mixtures can influence both the droplet size distribution and the mass of nebulized aerosol delivered to patients.[42] Compared to the usual aerosol delivery technique, heliox-driven salbutamol nebulization may shorten the stay in the emergency department.[43] A recent bench study also suggests that heliox may improve aerosol delivered to pediatric patients through a high-flow nasal cannula.[44]

Carbon Dioxide

Historically, rebreathing carbon dioxide from a paper bag was once thought to relieve anxiety attacks. Ironically, the literature reports carbon dioxide inhalation can induce an emotion in humans closely replicating spontaneous panic attacks, as defined by current psychiatry nosology.[45] Carbon dioxide/oxygen mixtures, also known as **carbogen**, have been used to terminate seizures (petit mal), improve regional blood flow by dilating vessels in the brain of stroke victims, and encourage ophthalmic artery blood flow.[46] Introducing small amounts of carbon dioxide into inspired gas before and after cardiac surgery on infants with hypoplastic left heart syndrome can help limit pulmonary blood flow by increasing pulmonary vascular resistance. A system to deliver carbon dioxide/oxygen mixtures has been described by Chatburn and Anderson.[47]

Nitric Oxide

Inhaled **nitric oxide** (iNO) has been used as a selective (i.e., affecting the lung rather than the systemic vasculature) pulmonary vasodilator. It has been approved by the FDA for use in conjunction with ventilatory support for the treatment of term and near-term (>34 weeks) neonates with hypoxic respiratory failure associated with clinical or echocardiographic evidence of pulmonary hypertension to improve oxygenation and reduce the need for extracorporeal membrane oxygenation. When delivered along with oxygen, nitric oxide forms small amounts of nitrogen dioxide, a toxic gas. The levels of nitric oxide generated are dependent on F_{IO_2}, nitric oxide dose, and contact time between nitric oxide and oxygen. Therefore, delivery methods designed to minimize nitrogen dioxide generation and careful dosing of nitric oxide and monitoring of nitrogen dioxide are important.

The INOmax DSIR system, from Mallinckrodt Pharmaceuticals, is a commercially available device for delivering inhaled nitric oxide that is compatible with most ventilators in the United States (**Figure 2-32**). This device can be used with conventional and nonconventional ventilation (e.g., high-frequency jet ventilation and high-frequency oscillatory ventilation) or noninvasively with devices such as a high-flow nasal cannula or nasal CPAP system. This unit can be adapted to provide iNO therapy during interfacility air and ground transport (**Figure 2-33**).

The INOmax DSIR system delivers nitric oxide from an 88 or a D-size compressed gas cylinder containing

FIGURE 2-32 INOmax DSIR delivery system.
Courtesy of © Ikaria, Inc.

FIGURE 2-33 INOmax DSIR delivery system adapted for use in transport.

800 parts per million (ppm) of nitric oxide (balance gas is nitrogen). During mechanical ventilation, the gas is introduced into the inspiratory limb on the dry side of the patient circuit through a port on an injector module that also contains a hot-film flow sensor, which measures ventilator gas flow. Positioning the injector module in this manner allows for adequate mixing time of this specialty gas along the inspiratory limb of the circuit and the delivery of a more stable dose to the patient. Independent of the injector module position, this nitric oxide delivery system adds a proportional amount of nitric oxide gas, which is based on the set dose and the ventilator flow rate. More gas is added to the inspiratory limb as the iNO dose is increased, which, in turn, dilutes the concentration of oxygen delivered to the patient. **Table 2-4** provides a detail of the dilution effect of iNO dosing.

As flow in the ventilator circuit is measured, the nitric oxide is injected in a constant proportion to inspiratory flow to deliver a precise dose, from 0.1 to 80 ppm. The delivery system monitors inspired gas concentrations for oxygen, nitric oxide, and nitrogen dioxide, with an alarm setting for each (**Figure 2-34**).

Because the combination of oxygen and nitric oxide forms nitrogen dioxide, a toxic gas by-product, the quantity of nitrogen dioxide within the system requires vigilant monitoring. Nitrogen dioxide concentrations are influenced by the delivery system and the amount of time left for iNO to oxidize within the circuit.[48] This is of particular interest when a self-inflating resuscitator is used to deliver iNO during manual ventilation or an anesthesia machine is used to deliver iNO. During the delivery of iNO with high concentrations of oxygen, such as 90%, nitrogen dioxide concentrations of 5 ppm can form in less than 2 seconds.[49] This system also has a number of other alarms for delivery designed to minimize interruption of therapy. In the event of a malfunction, the system also has two pneumatically powered systems to provide continuous delivery of nitric oxide.

TABLE 2-4
The Dilution Effect Increasing Doses of iNO Have on F_{IO_2}

iNO Dose (ppm)	Oxygen Diluted from the Intended Concentration (%)
20	10
40	5
80	10

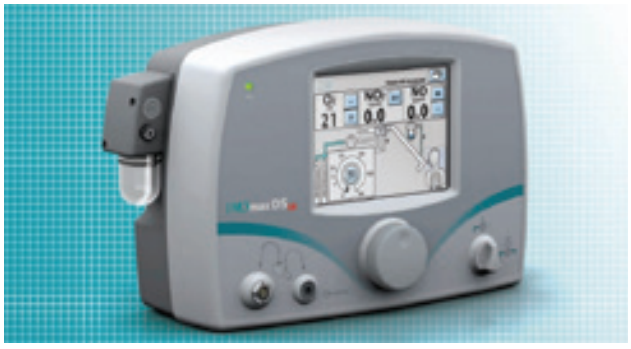


FIGURE 2-34 The INOmax DSIR control panel shows the monitored parameters (F_{IO_2} and nitric oxide) and the iNO dose.

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