Delivering oxygen to patients

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Oxygen delivery is often discussed in the context of passage of oxygen from the airway to the tissues. Delivery of oxygen to the patient's airway is less frequently discussed and maybe less well understood. This article aims to clarify some of the confusion surrounding this important subject and so enable safer and more accurate oxygen prescription.

Historical perspective

Scheele, a Swedish apothecary, first discovered oxygen in 1772. However, Joseph Priestley is usually credited with this finding because he was the first to describe it in 1775 in his work entitled *Experiments and Observations on Different Kinds of Air*. He referred to this new gas as 'dephlogisticated air' and at that time noted: '...it may be conjectured, that it might be peculiarly salutary to the lungs in certain morbid cases'. The first recorded case of inhaled oxygen being used in medicine was by the French physician Caillens in 1783. Over the next hundred years, the popularity and credibility of the therapeutic use of oxygen fluctuated.

One early reference to specially designed masks for the administration of oxygen is found in the work of Hill published in the *British Medical Journal* in 1912. Prior to this, descriptions of a multitude of methods of application of oxygen can be found including via the stomach for resuscitation, and per rectum and per vaginum for conditions such as cholera and inflammatory diseases. However, in 1914, Howitt wrote: 'In my experience the old method of inhalation was a failure'. He went on to extol the virtues of subcutaneous injection of oxygen for a variety of diseases including eclampsia, pertussis, diabetes, emphysema and even asystole! He declared the method of raising a subcutaneous lump as large as the closed fist as the formation of an artificial lung.

The works of Haldane (1917) united the physiological and theoretical basis for inhalational oxygen therapy. Furthermore, it dispelled many of the myths and prejudices of the day and, at last, it became a fully accepted therapy. In support of Haldane's work, Meltzer, writing in the *Journal of the American Medical Association*, also went on to say that the failure of some practitioners to see any favourable effect 'is probably due essentially to the inefficient method of administration'. Meltzer's statement still holds true today where the effective, accurate and efficient administration of oxygen is not seen universally, often due to confusion about the various devices and methods for its delivery.

This article classifies oxygen therapy devices according to flows and in relation to the patient's peak inspiratory flow. It discusses the effect of peak inspiratory flow on the fraction of oxygen actually received by the patient's airways.

Classification of oxygen therapy devices

There are a number of methods of classifying devices that deliver oxygen to the patient's upper airway. These include: (i) fixed versus variable performance; (ii) 'patient-dependent' versus 'patient-independent'; and (iii) low versus high gas flows. The fixed performance systems are usually considered as 'patient-independent' because the patient receives a constant, predetermined inspired oxygen concentration ($F\text{IO}_2$) regardless of changes in respiratory parameters. The variable performance systems are 'patient-dependent' because the patient receives a variable $F\text{IO}_2$ as their respiratory parameters change.

Table 1 classifies oxygen therapy devices by considering the total gas flow delivered to

Key points

In order to administer controlled oxygen therapy, it is necessary to understand the relationship between the patient's peak inspiratory flow and the flow of gas delivered.

When the flow of gas delivered to the patient exceeds peak inspiratory flow, the oxygen concentration received is **patient independent**.

When the flow of gas delivered to the patient is less than peak inspiratory flow, the oxygen concentration is **patient dependent** (unless there is a tight fitting mask with a reservoir).

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Table 1 Classification of oxygen therapy devices

	Low flow	High flow
Fixed performance devices (patient-independent)	Tight fitting with reservoir *e.g.* anaesthetic systems, face mask with reservoir bag	Flow exceeds peak inspiratory flow High air flow oxygen enrichment devices (HAFOE), *e.g.* Ventimask, air entrainment with humidification
Variable performance devices (patient-dependent)	Nasal cannula Hudson mask	Flow is less than peak inspiratory flow High air flow oxygen enrichment devices (HAFOE), *e.g.* Ventimask, air entrainment with humidification

the patient. While there is no defined cut-off point between low and high flow, it is reasonable to place it at about 10–15 litre min^{-1}. Low flow systems can deliver a known F_{IO_2} when there is a tight fitting mask and a reservoir, such as anaesthetic breathing systems. High flow devices become patient-independent when the flow exceeds the patient's peak inspiratory flow. Conversely, when the flow is less than the peak inspiratory flow, even the high flow devices become patient-dependent. A detailed explanation of this is given in the next section.

Importance of peak inspiratory flow

Imagine an intubated patient breathing spontaneously from a T-piece with no reservoir. If the fresh gas flow (FGF) was zero, all the inspiratory gas would be room air. On the other hand, if the FGF was a ludicrous 200 litre min^{-1}, all the inspiratory gas would be taken from the FGF and thus have the F_{IO_2} of the fresh gas. If we now decrease the FGF from 200 litre min^{-1}, there will be a point at which the FGF will not meet the patient's requirements. Below this flow, the patient will start to entrain room air which will dilute the F_{IO_2} of the fresh gas. This occurs when the FGF is less than the peak inspiratory flow.

Let's put some real numbers to this proposition. A respiratory rate of 10 breaths min^{-1} will make each respiratory cycle 6 sec. An inspiratory-to-expiratory ratio of 1:2 will give an inspiratory time of 2 sec. If the tidal volume is 500 ml, this must be inspired during the 2 sec. Therefore, 0.25 litre sec^{-1} or 15 litre min^{-1} represents the mean inspiratory flow. If patients breathed with a square wave pattern, this would also be the peak inspiratory flow. However, the breathing pattern is more complicated. Initially the flow is slow, it accelerates and then declines at the end of inspiration. Thus, the peak flow must exceed the mean flow probably reaching about 30–40 litre min^{-1} (Fig. 1).

Let us return to our intubated patient. Imagine he/she receives a FGF of 15 litre min^{-1}. At the start of inspiration, all inspiratory gas will be taken from FGF. However, when the inspiratory flow exceeds 15 litre min^{-1}, entrainment of room

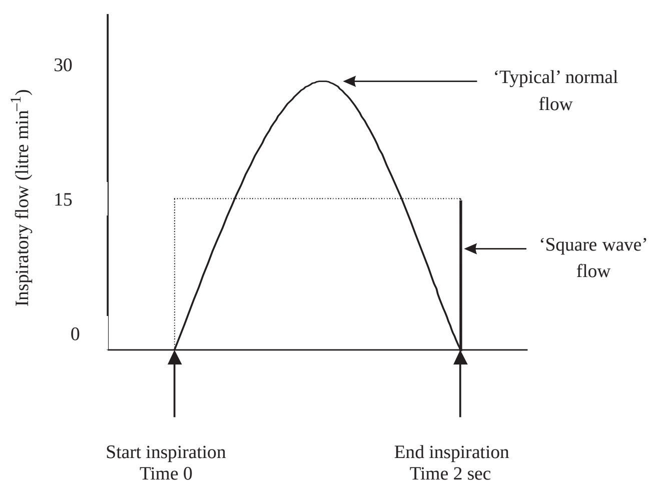

Fig. 1 Inspiratory flow pattern.

air will occur. After this point, the F_{IO_2} lies at some unknown value between that of the fresh gas and room air.

A patient with a face mask performs in a similar manner to that of an intubated patient without a reservoir on the T-piece. Therefore, in order to deliver a known and fixed F_{IO_2} to the patient via a face mask, the FGF should also exceed peak inspiratory flow.

Low flow devices

Anaesthetic circuits deliver a known F_{IO_2} because there is a reservoir and they are tight fitting. Nasal cannulae deliver a small flow of oxygen at a concentration of 100% (1–3 litre min^{-1}) into the naso-pharyngeal space. When the patient inspires, the oxygen is diluted with room air. The degree of dilution depends on the inspiratory flows. Simple face masks (*e.g.* Hudson mask) deliver oxygen at a concentration of 100% to the face. When the patient inspires, the oxygen is diluted with room air. The degree of dilution also depends on inspiratory flows. In both these examples, the actual F_{IO_2} delivered into the airways is variable and dependent on the peak inspiratory flow and oxygen flow.

High flow devices

High flow devices function by using pressurised oxygen to drive a venturi which entrains air, according to the Bernoulli effect. In the Ventimask, the venturi is part of the mask so that air is entrained into the mask, close to the patient. The oxygen is supplied to the mask through narrow bore oxygen tubing under pressure. The masks are colour-coded and labelled with the inspired oxygen concentration that they will deliver and the flow of oxygen required to achieve this.

An alternative is to have the venturi situated away from the patient close to the oxygen supply. The mixed gas is now at much lower pressure and is supplied through a wide bore low resistance tube. This method also enables a humidification device to be incorporated and a dial to adjust the $F\text{IO}_2$. However, confusion often arises under these circumstances. Yes, the $F\text{IO}_2$ delivered to the face mask is what is set on the dial. But no, it does not guarantee that this is the $F\text{IO}_2$ that reaches the patient's airway. If the FGF exceeds peak inspiratory flow, all is well. However, if the FGF falls below the peak inspiratory flow, further air entrainment will take place, thereby reducing the actual $F\text{IO}_2$ that the patient receives.

Flows from a venturi

The venturi oxygen delivery device has two variables – oxygen flow and the entrainment ratio. The latter is set by the manufacturer or the user. Back pressure or suction will change the entrainment ratio and/or entrain extra air from the exit path. Assuming all the oxygen takes part in the total flow, it is possible to derive a mathematical equation which will calculate the amount of air entrained. Total flow can then be derived by summing the flows of oxygen and air. Entrained air flow is given by the equation:

$$\text{Entrained air flow} = \frac{O_2 \text{ flow from wall} \times (1 - F\text{IO}_2)}{F\text{IO}_2 - 0.2}$$

An alternative form of this equation is to consider the ratio of the oxygen flow to the air entrained:

$$\frac{O_2 \text{ flow from the wall}}{\text{Entrained air flow}} = \frac{F\text{IO}_2 - 0.2}{1 - F\text{IO}_2}$$

For example, if the oxygen flow is 10 litre min^{-1} and $F\text{IO}_2$ 0.6, the ratio will be 1:1; *i.e.* for each litre of oxygen, 1 litre of air will be entrained.

Table 2 Total gas flows with variable $F\text{IO}_2$

$F\text{IO}_2$ (litre min^{-1})	Oxygen flow (driving) (litre min^{-1})	Air flow (entrained) (litre min^{-1})	Total flow (litre min^{-1})
1.0	10	0	10
0.6	10	10	20
0.6	20	20	40
0.5	10	17	27
0.5	15	25	40
0.4	10	30	40
0.24	2	38	40

The effects of varying the $F\text{IO}_2$ and the driving flow of the oxygen are illustrated in Table 2. When the $F\text{IO}_2$ is 1.0, there is no air entrainment. Thus, if the patient's peak inspiratory flow exceeds the oxygen flow, dilution will occur. Oxygen flow is usually set below 10 litre min^{-1} on the wall flow meters because, at higher rates, the system tends to whistle and become 'noisy'.

When aiming to deliver an $F\text{IO}_2$ of 0.6, the flows of oxygen and entrained air are the same (an easy number to remember). If the wall oxygen flow is set to 15 litre min^{-1}, this gives a total gas flow of 30 litre min^{-1}, and it may only just meet the patient's peak inspiratory flow. Thus, further air entrainment will occur, which reduces the $F\text{IO}_2$ actually received by the patient. Furthermore, the group of patients who need a high $F\text{IO}_2$ are likely to have peak inspiratory flows higher than normal. In practice, the total gas flow can be increased by connecting the output flow from two air entrainment venturis together with a Y-piece. It is not until the $F\text{IO}_2$ is set at 0.4 that the flows become satisfactory with a wall oxygen flow of 10 litre min^{-1}.

Further reading

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See multiple choice questions 29–31.