The History of Oxygen Therapy

Human life is inconceivable with the oxygen molecule. Its absence means death, its presence life. Oxygen was discovered by Joseph Priestley in Britain on August 1, 1774. He defined his discovery as pure air and remarked, “Who can tell but that, in time, this pure air may become a fashionable article in luxury.” Around the same time, Swedish chemist Carl Wilhelm Scheele, unaware of Priestley’s work, also isolated the oxygen molecule, although all the credit has gone to Priestley. It was not until several years later, however, that this new “air” received its definitive name, oxygene—chosen by Antoine Lavoisier, a friend of Priestley’s who was familiar with his work. The 19th century saw the first medical uses of oxygen. The earliest written report of its therapeutic efficacy came in 1885, when George Holtzapple described how he had successfully used oxygen to treat a young man from New York with respiratory distress syndrome secondary to pneumonia. Physicians had been using oxygen for many purposes before this date, however. At the beginning of the 20th century, English physiologist John Scott Haldane demonstrated the harmful effects of hypoxemia (morning headache, tachycardia, and tachypnea) for the first time and predicted that oxygen would soon be used throughout hospitals to treat these symptoms. This was indeed the case, thanks in part to the findings of Alvin Barach, the father of modern oxygen therapy. In 1922, Barach published an article describing the use of oxygen in the

Oxygen-conserving devices include transtracheal catheters, reservoir cannulas, and demand oxygen delivery systems. They are designed to extend the amount of time portable oxygen cylinders will last and correct hypoxemia with a lower flow of oxygen. Transtracheal catheters increase the fraction of inspired oxygen by delivering oxygen directly to the trachea, bypassing the dead space of the oropharynx and improving the efficiency of the upper airway as a reservoir. Reservoir cannulas increase the fraction of inspired oxygen at the beginning of the inspiratory phase. Demand oxygen delivery systems have a valve that is activated during inspiration, meaning that oxygen is only delivered during this stage of the respiratory cycle. Each system has advantages and disadvantages arising from differing design features. Prescription should be based on individual tests in all cases to ensure optimal oxygen delivery during rest, exercise, and sleep.

Key words: Oxygen conservation. Transtracheal catheter. Reservoir cannula. Demand oxygen delivery systems.

Sistemas de ahorro de oxígeno. Una realidad olvidada

Los sistemas de ahorro de oxígeno agrupan el catéter transtraqueal, las cánulas reservoirio y los sistemas a demanda. Su objetivo es aumentar la autonomía de las fuentes de oxígeno portátiles consiguiendo una corrección de la hipoxemia con menor flujo de oxígeno. El catéter transtraqueal aumenta la fracción inspiratoria de oxígeno al proporcionar oxígeno directamente en la tráquea, lo que evita el espacio muerto de la cavidad orofaríngea y favorece que la vía aérea superior actúe como reservorio. Las cánulas reservoirio aumentan la fracción inspiratoria de oxígeno al inicio de la inspiración. Los sistemas a demanda cuentan con una válvula que se activa con la inspiración, de modo que se administrará oxígeno sólo durante esta fase del ciclo respiratorio. Debido a sus diferentes características, cada sistema presenta ventajas e inconvenientes. Para su correcta prescripción debe ajustarse individualmente el flujo de oxígeno tanto en reposo como durante el ejercicio o el sueño con las pruebas pertinentes.

In later years, spurred on by knowledge he had acquired while working in a pulmonary physiology laboratory during World War II, Barach developed a continuous oxygen delivery system (long-term oxygen therapy) that was inspired by the design of the oxygen masks used by fighter pilots during the war. His ingenuity was further revealed in the mid-1950s when he designed a system consisting of small oxygen tanks that could be fitted to patients’ waists to provide them with oxygen outside the home (ambulatory oxygen therapy). In 1956, Cotes and Gilson published an article describing how a group of patients demonstrated clinical improvement after they had been administered oxygen during exercise.

The idea of controlling the delivery of oxygen emerged in the 1960s, when Campbell designed an oxygen mask based on the Venturi effect that made it possible to control the fraction of inspired oxygen (FiO₂) delivered. The aim of the system was to gain greater control of the amount of oxygen administered to patients with chronic obstructive pulmonary disease (COPD), as several of these had developed complications related to the use of high flows. Around the same time, several groups of investigators, including a group led by Petty, conducted the first systematic studies of chronic oxygen therapy; they reported improved exercise tolerance and a reduction in polycythemia and pulmonary hypertension. Shortly afterwards, growing evidence pointed to a reduction in hospitalization and mortality among patients treated with oxygen.

Interest in this direction prompted further landmark studies: the Nocturnal Oxygen Therapy Trial (NOTT) and a study of long-term domiciliary oxygen therapy by the British Medical Research Council (MRC). The NOTT, which was conducted in the United States of America, compared survival and quality of life in COPD patients on continuous oxygen (17.4 hours a day on average) and in COPD patients on nocturnal oxygen (12 hours a day). The MRC study was also conducted in the setting of COPD but analyzed differences between patients who received no oxygen therapy and patients who received an average of 15 hours of oxygen a day. Both studies reported better survival in patients who received oxygen and, in addition, showed that survival was directly correlated to the number of hours of oxygen received. The studies laid the foundation for the prescription of long-term home oxygen therapy for COPD patients. The use of such therapy is also extended to patients with other types of chronic lung disease even though its efficacy in other settings has not yet been fully demonstrated.

### Oxygen Sources

The main sources of oxygen are compressed gas, concentrators, and liquid oxygen. Table 1 shows the main characteristics of each.

- **Compressed Gas Cylinders**
  - Sedentary patients
  - Complements stationary systems and allows patients to be mobile
  - Allows patients to move outside the home
  - Requires mains electricity supply
  - Heavy
  - Requires mains electricity supply
  - Short duration
  - Not refillable
  - Medium
  - Loss of efficacy with high oxygen flows
  - Does not allow patients to move outside the home
  - Requires mains electricity supply
  - Refillable from base unit
  - Medium
  - Mobile patients

- **Portable Gas Cylinder**
  - Complements stationary systems and allows patients to be mobile
  - Allows patients to move outside the home
  - Requires mains electricity supply
  - Heavy
  - Requires mains electricity supply
  - Short duration
  - Not refillable
  - Medium
  - Loss of efficacy with high oxygen flows
  - Does not allow patients to move outside the home
  - Requires mains electricity supply
  - Refillable from base unit
  - Medium
  - Mobile patients

- **Oxygen Concentrator**
  - Patients with restricted mobility and oxygen requirements
  - Does not require mains electricity supply
  - Satisfactory duration
  - Requires mains electricity supply
  - Medium
  - Low

- **Liquid Oxygen**
  - Mobile patients
  - Satisfactory duration
  - Requires mains electricity supply
  - High

### Table 1

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Compressed Gas Cylinder</th>
<th>Portable Gas Cylinder</th>
<th>Oxygen Concentrator</th>
<th>Liquid Oxygen</th>
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<tbody>
<tr>
<td><strong>Indications</strong></td>
<td>Sedentary patients</td>
<td>Complements stationary systems and allows patients to be mobile</td>
<td>Patients with restricted mobility and oxygen requirements</td>
<td>Mobile patients</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Silent</td>
<td>Allows patients to move outside the home</td>
<td>Does not require mains electricity supply</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Requires mains electricity supply</td>
<td>Heavy</td>
<td>Loss of efficacy with high oxygen flows</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stationary</td>
<td>Requires mains electricity supply</td>
<td>Does not allow patients to move outside the home</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short duration</td>
<td>Not refillable</td>
<td>Requires mains electricity supply</td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
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A recent Cochrane library meta-analysis concluded that ambulatory oxygen improved exercise performance in COPD patients with moderate to severe disease. Improved exercise capacity has also been demonstrated in COPD patients with normal daytime oxygen saturation ($\text{PaO}_2 > 600$ mm Hg) who received oxygen during a pulmonary rehabilitation program. Despite this evidence, however, liquid oxygen has taken a back seat to other oxygen delivery systems. A recent Cochrane library meta-analysis concluded that transtracheal catheters can yield oxygen savings of around 50% during rest and 30% during exercise. They have also been shown to reduce patients’ work of breathing and dyspnea by reducing minute ventilation, and to improve hemodynamic response. All these advantages have a considerable impact on patients’ health-related quality of life.

**Oxygen-Conserving Devices**

Oxygen-conserving devices appeared in the mid-1980s in order to increase the duration of portable oxygen systems by reducing the amount of oxygen they consumed. There are 3 types of oxygen-conserving devices: transtracheal catheters, reservoir cannulas, and demand oxygen delivery systems. (See Table 2 for their main characteristics.) Because standard nasal cannulas are known to be an inefficient means of oxygen delivery as only 15% to 20% of the oxygen they supply actually takes part in gas exchange, oxygen-conserving devices were conceived to both reduce and optimize oxygen use. It has been estimated that when a small gas cylinder is used with an oxygen-conserving device, the cylinder can last up to 3-fold longer than when used with conventional nasal cannulas. Not only do such devices optimize oxygen delivery, but they also make portable oxygen systems a more cost-effective option. The main characteristics of the main oxygen-conserving devices are summarized in Table 2.

**TABLE 2**

<table>
<thead>
<tr>
<th>How it works</th>
<th>Reservoir Cannula</th>
<th>Demand Oxygen Delivery System</th>
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<tr>
<td>Indicates</td>
<td>Only delivers oxygen during inhalation (at beginning of inhalation)</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td>PORTABLE. REFRACTOR HYPOXEMIA</td>
<td></td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Easy to use</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Medium</td>
</tr>
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**Transtracheal Catheters**

Transtracheal catheters deliver oxygen directly to the trachea through a small catheter measuring between 1.6 mm and 2 mm in diameter that is inserted percutaneously between the second and third tracheal rings. By bypassing the dead space of the oropharynx and using the upper airway as a reservoir, the system increases the $\text{FiO}_2$ and produces similar saturation levels to standard systems, but at lower oxygen flow rates. It has been estimated that transtracheal catheters can yield oxygen savings of around 50% during rest and 30% during exercise. They have also been shown to reduce patients’ work of breathing and dyspnea by reducing minute ventilation, and to improve hemodynamic response. All these advantages have a considerable impact on patients’ health-related quality of life.

**Reservoir Cannulas**

Reservoir cannulas were introduced in the mid-1980s to improve the efficacy of standard nasal cannulas. By
increasing the volume of oxygen delivered at the beginning of the inspiratory phase, they achieve a greater FiO\textsubscript{2}, in the tidal volume that participates in gas exchange. The reservoir contains a membrane that is activated when the patient exhales. A bolus of between approximately 30 and 40 mL of the incoming oxygen is stored in the reservoir and delivered at the beginning of inhalation. This oxygen is normally wasted in standard systems. There are 2 models of reservoir cannula: the Oxymizer, which is a moustache-style cannula, and the Oxymizer Pendant, which hangs on the chest and is connected to the nose via 2 larger-than-normal prongs (Figure 1). Reservoir cannulas conserve oxygen because they produce adequate oxygen saturation levels with lower flow rates.\textsuperscript{35} They are used to increase the duration of portable oxygen systems and to optimize treatment in patients using stationary sources of oxygen as these are not always able to provide the required flow of oxygen with conventional delivery systems. Reservoir cannulas, however, can be problematic in patients that have high respiratory rates (patients with restrictive diseases, for example) as they tend to breathe through their mouth. This reduces the efficacy of the devices\textsuperscript{35} and it is therefore important to teach these patients to always breathe through their nose. Although reservoir cannulas are more effective than standard ones, a classic study by Clairborne and colleagues\textsuperscript{37} showed that they were rejected by certain patients on the grounds of being less comfortable (in nose and on ears due to their thicker, heavier design) and less esthetic. Numerous other studies, however, have shown that reservoir cannulas are an efficient means of conserving oxygen and ensuring adequate oxygen saturation levels.\textsuperscript{36-39} Nevertheless, despite their similarity to standard nasal cannulas and the fact that they do not cause major complications, reservoir cannulas are also used very little in Spain.

**Demand Oxygen Delivery Systems**

Demand oxygen delivery systems were developed at the beginning of the 1980s and are perhaps the most popular oxygen-conserving system used today. Like reservoir cannulas, they were designed to improve the efficacy of standard nasal cannulas by rationing the amount of oxygen delivered during the different phases of the respiratory cycle. Oxygen flow is controlled by a valve that opens whenever the unit detects negative inspiratory pressure (Figure 2). This means that oxygen is only delivered during the inhalation phase of the respiratory cycle and wastage during exhalation is avoided. The system was further enhanced with the introduction of 2 separate strategies designed to reduce the amount of oxygen that accumulates in the dead space and improve gas exchange. The first strategy delivers a fixed bolus of oxygen, whose volume can be increased by changing the numerical settings on the device; delivery is at the beginning of inhalation only. The second strategy delivers a smaller bolus of oxygen at the beginning of inhalation, but this is then followed by a continuous flow of oxygen, generally at lower concentrations than those used in conventional systems. A common misconception among doctors is that demand oxygen delivery systems administer a continuous flow of oxygen, just like conventional systems. This is not the case, however: they deliver a volume of oxygen that is estimated to be equivalent to the volume that participates in gas exchange. This means that oxygen is saved and adequate saturation levels ensured.

Demand oxygen delivery systems are mostly used with patients on portable oxygen therapy. The main strengths of the system are that it is esthetic and has been incorporated into the majority of liquid oxygen portables on the market (Figure 2). This has resulted in smaller, lighter tanks that last for the same amount of time as their predecessors, and this has obvious benefits for the patient. The system’s main drawback is that it cannot be used to correct hypoxemia in patients who require high oxygen flow rates. Inefficiency can be increased by valve sensitivity, respiratory rate, and mouth breathing, but several studies have shown the system to be efficient during rest, exercise, and sleep.\textsuperscript{40-45} Moreover, Cuvelier and colleagues\textsuperscript{46} found that

![Figure 1. Reservoir cannula: Oxymizer (left) and Oxymizer Pendant (right).](image1)

![Figure 2. Demand oxygen delivery system: valve fitted on liquid oxygen tank (left) and independent valve (right).](image2)
ventilation and neurophysiological parameters were essentially equivalent in patients with moderate to severe COPD regardless of whether they received oxygen on demand or continuous flow oxygen. Demand systems are efficient, convenient, and easy to use and as such, are an ideal choice for patients on ambulatory oxygen therapy.

Prescribing Oxygen-Conserving Devices

It is important to readjust all previously established oxygenation settings when prescribing an oxygen-conserving device. Given that the 6-minute walk test has been shown to provide the most accurate indication of desaturation, this test should be performed using the new device to ensure that the settings are correctly adjusted for walking. When used for long-term home oxygen therapy (whether from portable liquid oxygen or stationary systems), daytime and nighttime settings should also be adjusted to prevent desaturation.

Demand oxygen delivery systems are unique in that no 2 models use the same volume of oxygen. Johann and colleagues,49 for example, observed significant variations in PaO, resulting from the use of 2 different models. This observation was confirmed in a recent study by Bliss and colleagues,50 who compared different systems on the market using a breathing simulator. They found that the volume of oxygen administered varied from model to model and that there was no equivalence between models. It is therefore important to adjust oxygenation settings for rest, exercise, and sleep to the patient’s needs whenever a system or model is changed.

A Forgotten Resource

Oxygen-conserving devices are an efficient alternative to standard oxygen delivery systems, and they are particularly suited to mobile patients as they increase the amount of time portable systems will work. They are also suited for optimizing oxygen therapy in patients with refractory hypoxemia. Each device has advantages and disadvantages arising from differing design features and it is important to carefully study these before deciding which one is best suited to each patient. Prescription should be based on individual tests in all cases to ensure optimal oxygen flow rates for rest, exercise, and sleep.

Oxygen-conserving devices, however, are used little in Spain. The reasons are many and complex and include cultural and practical considerations. Most patients in our setting, and particularly those with respiratory disorders, are highly sedentary. They rarely leave home and very few patients with chronic respiratory diseases use ambulatory oxygen therapy to perform activities of daily living. This is not the case in all countries, however. In the United States, for example, large grocery stores have shopping carts fitted with supplemental oxygen and patients with breathing difficulties are generally more active socially (they go out unaided, go on holidays, etc.) In Spain, home oxygen therapy patients have serious difficulties performing activities like traveling by plane. Consequently, chronic respiratory disease patients in our setting tend to be inactive and this results in a lower demand for devices that facilitate the management of ambulatory oxygen therapy. Another factor that works against the use of oxygen-conserving devices is the general impression that they are of little use, a throwback to the early days when they were seen as inefficient and complicated. And then there is their cost. Stationary systems, and concentrators in particular, are more popular with suppliers and health care authorities as they require less ongoing support and cost less. The truth is, however, that oxygen-conserving devices reduce the cost of portable oxygen systems (liquid portables mainly) and considerably improve the quality of life of certain groups of patients. This alone should make them obligatory throughout Spain’s health care system.

Oxygen-conserving devices have somehow slipped into oblivion. On the one hand, we have a series of devices that are relatively easy to use and, although they require a little learning on the part of the patient, can considerably improve health-related quality of life and generate substantial savings all round. On the other hand, however, we have a respiratory patient population that is becoming increasingly sedentary and little effort has been made to promote the use of these devices. The result is that they are hardly ever employed. We need to invest greater effort in educating doctors, patients, medical equipment suppliers, and public health care authorities to bring about a change in behavior. In our opinion, it is an effort worth making, and the sooner it is made, the better.

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