REVIEW ARTICLE

Oxygen-Conserving Systems: A Forgotten Resource

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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 reservorio 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 reservorio 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 administra 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.

Palabras clave: *Ahorro de oxígeno. Catéter transtraqueal. Cánulas reservorio. Sistemas a demanda.*

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.[1] 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,[2] 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.[4] 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

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Manuscript received April 11, 2006. Accepted for publication May 16, 2006.

treatment of pneumonia (short-term oxygen therapy).[6] 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).[7] In 1956, Cotes and Gilson[8] 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[9] designed an oxygen mask based on the Venturi effect that made it possible to control the fraction of inspired oxygen (FiO_2) 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.[10,11] Shortly afterwards, growing evidence pointed to a reduction in hospitalization and mortality among patients treated with oxygen.[12,13] Interest in this direction prompted further landmark studies: the Nocturnal Oxygen Therapy Trial (NOTT)[14] and a study of long-term domiciliary oxygen therapy by the British Medical Research Council (MRC).[15] 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.[16]

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 were the first delivery systems used. Though still widely used, they have a major drawback: their size and weight. Although this problem has been partly overcome with the introduction of portable models, gas cylinders can seriously hinder patient mobility, even around the home. Oxygen concentrators appeared in the early 1970s. They work by concentrating the oxygen in the air and separating it from nitrogen through a series of filters, and their advantage is that they work independently of other systems (unlike gas cylinders they do not need to be refilled periodically from a base unit). However, they need to be connected to the mains electricity supply, a major drawback that limits patient mobility. Liquid oxygen was first used for home oxygen therapy purposes in 1965, when Union Carbide, working with Petty, developed a small portable system.[17] Its size and weight were suited to patients' needs and the system could be refilled from a base unit. Although liquid portables have a limited duration (that depends mostly on the flow rate prescribed) they are an effective means of ensuring adequate oxygen saturation during activities of daily living both inside and outside the home.

Liquid oxygen systems have been shown to improve quality of life for patients requiring home oxygen therapy by affording them greater mobility and independence in activities of daily living at home and in the community.[18]

TABLE 1
Main Characteristics of Oxygen Sources

	Compressed Gas Cylinder	Portable Gas Cylinder	Oxygen Concentrator	Liquid Oxygen
Indications	Sedentary patients	Complements stationary systems and allows patients to be mobile	Patients with restricted mobility and low oxygen flow requirements	Mobile patients
Advantages	Silent	Allows patients to move outside the home	Does not require mains electricity supply	Allows patients to move outside the home Satisfactory duration Refillable from base unit
Disadvantages	Requires mains electricity supply. Stationary	Heavy Requires mains electricity supply. Short duration Not refillable	Loss of efficacy with high oxygen flows Noisy Does not allow patients to move outside the home Requires mains electricity supply	Requires mains electricity supply
Cost	Medium	Medium	Low	High

TABLE 2
Main Characteristics of Oxygen-Conserving Devices

	Transtracheal Catheter	Reservoir Cannula	Demand Oxygen Delivery System
How it works	Reduces dead space Uses upper airway as reservoir	Stores oxygen during exhalation and delivers it at beginning of inhalation	Only delivers oxygen during inhalation (at beginning mainly)
Indications	Portable. Refractory hypoxemia	Portable. Refractory hypoxemia	Portable
Advantages	Improves lung function parameters	Easy to use	Adapted to liquid oxygen tanks
Disadvantages	Invasive Needs to be replaced periodically	Not very comfortable	Reduced efficacy at high respiratory rates
Cost	High	Low	Medium

A recent Cochrane library meta-analysis concluded that ambulatory oxygen improved exercise performance in COPD patients with moderate to severe disease.[19] Improved exercise capacity has also been demonstrated in COPD patients with normal daytime oxygen saturation (PaO_2 >600 mm Hg) who received oxygen during a pulmonary rehabilitation program.[20] Despite this evidence, however, liquid oxygen has taken a back seat position behind oxygen concentrators, and to a lesser extent, compressed gas cylinders.[21,22] The latter are preferred by medical equipment suppliers as they involve fewer costs and this is a policy that is openly welcomed by national health care systems.

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.[23] (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,[24] 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.[25] 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.

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 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.[26] They have also been shown to reduce patients' work of breathing and dyspnea by reducing minute ventilation,[27,28] and to improve hemodynamic response.[29] All these advantages have a considerable impact on patients' health-related quality of life.

Transtracheal catheters are principally designed to reduce oxygen waste in patients receiving ambulatory oxygen therapy, although Christopher and colleagues[30] also described their value in patients with refractory hypoxemia. Although transtracheal catheters are esthetically appealing as they can be easily concealed under clothing, they are frequently rejected by patients, mostly because they are an invasive method but also because they need special care, require training, and have to be replaced every 60 to 90 days in a hospital setting. The main complications associated with transtracheal catheters occur in the insertion area (subcutaneous emphysema, cellulitis, bleeding, etc).[31] Their use is absolutely contraindicated in patients with subglottic stenosis, vocal cord paralysis, severe coagulation disorders, and respiratory acidosis. Patients who are unable to care for their catheter should also not receive one, and they are relatively contraindicated in patients with bronchial hypersecretion or conditions that could prevent the scar from healing properly.

Even though transtracheal catheters were first used in medical practice over 20 years ago,[32] they are currently prescribed very rarely. There are 2 main reasons for this. First, they are not popular with patients, as demonstrated by Díaz-Lobato and colleagues,[33] who found that only 9% of their respiratory failure patients were willing to accept a transtracheal catheter for home use. Second, despite recent findings to the contrary,[34] doctors are under the impression that the catheters give rise to many complications.

To sum up, numerous studies have shown that, in the absence of contraindications, transtracheal catheters are the ideal choice for delivering a continuous 24-hour flow of oxygen in patients with normal activity levels.

Reservoir Cannulas

Reservoir cannulas were introduced in the mid-1980s to improve the efficacy of standard nasal cannulas. By

Figure 1. Reservoir cannulas: Oxymizer (left) and Oxymizer Pendant (right).

Figure 2. Demand oxygen delivery systems: valve fitted on liquid oxygen tank (left) and independent valve (right).

increasing the volume of oxygen delivered at the beginning of the inspiratory phase, they achieve a greater FiO_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.[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[36] 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 Clairbone and colleagues[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.[36,38,39] 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.[40-45] Moreover, Cuvelier and colleagues[46] found that 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,[47] 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,[48] for example, observed significant variations in PaO_2 resulting from the use of 2 different models. This observation was confirmed in a recent study by Bliss and colleagues,[49] 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 indicated 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.[50] 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.[51] 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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