Demand Oxygen Delivery during Exercise

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Nine hypoxemic patients with COLD, whose hypoxemia is aggravated by minimal exercise, volunteered for this study. Each subject underwent two treadmill exercise trials at two oxygen delivery settings, each on the DODS and SF delivery systems for a total of four exercise trials. We measured SaO₂ via ear oximetry and recorded oxygen usage per minute. We compared the oxygen usage required for the two techniques to achieve an SaO₂ of 90 percent. The results indicate that the mean oxygen requirement using the DODS to achieve an SaO₂ of 90 percent was 211.4 ml/min as compared to SF delivery which required 1,610.9 ml/min. This implies an oxygen savings advantage of the DODS over SF of 7:1. The fact that the DODS oxygen savings extends to exercise conditions lends support to its use in portable oxygen therapy. Widespread use of this and other oxygen savings techniques could result in significant cost savings while maintaining the desired benefits of supplemental oxygen administration.

Low flow oxygen therapy has long been regarded as beneficial to patients with chronic lung disease and hypoxemia. However, only recently have multicenter studies firmly established that oxygen therapy improves both life expectancy and quality of life.1,2 Now, with widespread application of pulmonary rehabilitation programs, portable or ambulatory oxygen is being prescribed in an increasing number of patients.3,4

Portable oxygen systems have afforded greater mobility to hypoxemic patients; however, these systems have some inherent disadvantages relating not only to the expense, but also to the amount of weight and bulk necessary to meet the patient’s oxygen needs over several hours.11 Unfortunately, patients with chronic lung disease are often weak and debilitated either by their disease pathology or by their sedentary lifestyles. Hence, these patients are often unable to carry their oxygen cannisters and must use a cart with wheels. These carts solve part of the weight problem, but, in exchange, add to the bulk and inconvenience of portable oxygen therapy.

If the patient’s oxygen supply requirements during ambulation could be reduced, portable oxygen systems could be smaller and lighter. For example, a standard E cylinder, which weighs about 16 lbs, provides about five hours of oxygen at 2 L/min of steady flow. If the same quantity of oxygen could be stretched seven times that of steady flow, the same cylinder would last 28 hours. Moreover, a small compressed gas cylinder which lasts one hour under steady flow conditions would be expected to last seven hours. Liquid oxygen savings will not be quite as great because of the inherent slow leak, but there are new, smaller and lighter weight liquid oxygen systems which have been redesigned to minimize the size of the leak.

The reduction in oxygen use can be translated into cost savings. While there are fixed costs of oxygen equipment and rental, the largest share of oxygen cost is attributed to oxygen usage. Thus, by reducing the total daily requirement for oxygen, patients can enjoy greater mobility while cutting the cost of oxygen therapy.

Reducing the oxygen usage required to maintain the patient’s oxygen saturation at an adequate level has been the subject of a number of investigations.18-28 Moreover, there are several devices and methods currently available to the patient designed to improve the efficiency of oxygen delivery. These include oxygen conserving nasal reservoir cannulas,19-25 trans-tracheal oxygen delivery,26-28 and electronic demand solenoid valve systems.24-28 The oxygen-saving rationale for using these devices is that steady-flow delivery occurs throughout the respiratory cycle despite the fact that most of the cycle consists of either exhalation or dead space inhalation. Consequently, most steady-flow oxygen is wasted to the atmosphere. A reasonable approach for accomplishing more cost-effective oxygen delivery would be to limit oxygen flow to the onset of inhalation.

We recently reported an electronic demand oxygen delivery system (DODS) which senses the beginning of inhalation and thereupon immediately delivers a short bolus of oxygen.29 The DODS improved the efficiency of oxygen delivery over steady flow by a factor of 7:1 during resting conditions. Since the most

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This research study was supported in part by Chad Therapeutics, Inc., Chatsworth, California, the Danziger Family Fellowship, and the Bay and Alpha Morrow Research Fund. Manuscript received April 24; revision accepted July 7.
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critical need to improve the efficiency of oxygen delivery is in portable oxygen therapy, we designed the present study to evaluate the DODS under conditions of dynamic exercise. Thus, we sought to determine whether oxygen savings of the DODS over steady flow would extend to exercise conditions.

**Material and Methods**

**Demand Oxygen Delivery System**

The DODS (Oxymatic, Chad Therapeutics, Inc, Chatsworth, CA) is a small, durable, 10 oz device, powered by a standard C-cell battery. It incorporates an electronically controlled solenoid valve and is interfaced between the patient and the liquid or gas oxygen source (Fig 1). The DODS senses the beginning of inhalation through the nasal cannula and thereupon directs the solenoid valve to open momentarily to deliver a 32 ± 2 ml bolus of oxygen. This delivery pulse is complete within 200 msec after the beginning of inhalation. It supports respiratory rates up to 40 breaths/min. The oxygen cannula is a standard double pronged nasal cannula which attaches to the DODS by a special connector that ensures the integrity of the connection. The DODS appears to be reliable in that the transducer can operate in any position, is insensitive to movement and wide variations in environmental temperatures, and has been bench-tested for more than one year of accurate delivery cycles. The current retail cost of the DODS sold as the Oxymatic is about $500, or can be rented for about $50 per month.

The amount of oxygen the DODS delivers to the patient can be adjusted by varying the number of breaths/min in which oxygen is pulsed to the patient. The DODS delivers a set pulse volume within a set time window and is adjustable only by altering the number of breaths allowed to occur between each delivery pulse. For example, on setting 1, an oxygen pulse occurs only once in four breaths, while, in contrast, setting 4 provides a pulse of oxygen upon each breath. DODS settings 1 through 4 are designed to provide oxygen delivery roughly equivalent to steady flow settings of 1 through 4 L/min respectively. The actual oxygen delivery per minute, using the DODS, is calculated by multiplying the 32 ml bolus times the number of pulses delivered per minute.

**Subjects**

Nine patients, five men and four women, with chronic obstructive lung disease who were mildly hypoxemic at rest and who had previously demonstrated arterial desaturation during low-level exercise were asked to volunteer for the study. Patients were recruited from the Pulmonary Rehabilitation Program of the University of Texas at Tyler Health Center. Subject characteristics are shown in Table 1. Flow volume loops (minimum of three) were obtained for each subject using a CPI model 220 rolling seal spirometer (CPI, Dayton, Ohio). On-line data acquisition and mathematical calculations were performed on a North Star Advantage Microcomputer (North Star Computers, San Leandro, CA). Lung diffusion measurements were made by the single breath technique and carbon monoxide was measured using a Tensor pulmonary diffusion system, model 7800 and Tensor gas chromatograph, model 78505 (Tensor, Inc, Irving, TX). The exercise screening was accomplished using a low-level, one minute incremental protocol on a treadmill (Quinton Q55) using an ear oximeter (Biox II A, Ohmeda Medical, Inc, Boulder, CO) to determine whether oxygen desaturation occurs during low-level exercise.

The subjects were all middle aged and had severe obstructive lung disease. The patients had no cardiovascular or orthopedic contraindications to low-level exercise. The treadmill used in the study was the same as the afore-mentioned screening treadmill. All studies were performed using low-level treadmill exercise sufficient to cause arterial oxygen desaturation under room air conditions. A typical treadmill setting for this patient group was 1 mph at zero grade for three minutes. Their range of oxygen saturation while exercising on oxygen was typically 85 to 95 percent and no subject was asked to endure prolonged exposure to exercise oxygen saturations less than 80 percent. Their medication schedules were unchanged except they were not allowed to take inhaled bronchodilators within one hour prior to the study and no patient smoked within two hours prior to the study. The patients signed an informed consent in accordance with the policies of the Institutional Review Board at the University of Texas Health Center at Tyler.

**Protocol**

All patients entered into this study were asked to undergo a total of four low-level treadmill exercise trials at two different oxygen flow settings, both on steady-flow oxygen and while using the DODS. The patients were allowed to relax at least ten minutes between exercise sessions so that their oxygen saturation could equilibrate to the next oxygen flow setting. Each exercise session lasted exactly three minutes and the exercise oxygen saturation was recorded immediately prior to completion of each exercise session.

Oxygen saturation was measured using a Biox IIA ear oximeter and continuously recorded on a strip chart recorder (Omniscribe Houston Instruments, Inc, Houston, TX). Steady flow oxygen was delivered through a Hudson nasal cannula (Hudson, Inc, Temecula, CA) and metered via a spirometrically calibrated rotometer and the DODS setting 1-4 was generally selected to match steady flow settings of 1-4 L/min. The DODS delivery was administered through

**Table 1—Subject Characteristics**

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<th>FVC (L)</th>
<th>FEV1/FVC (%)</th>
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<td>X</td>
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<td>SD</td>
<td>7.4</td>
<td>4.3</td>
<td>32.3</td>
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<td>17.1</td>
<td>2.5</td>
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Table 2

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Mean 59.4 ± 8.9 1111.1 ± 90.9 2055.6 ± 89.9 202.7 ± 92.1 376.9
SD 7.4 3.7 333.3 2.8 768.3 4.3 87.6 3.7 127.8

the same cannula as used during steady flow delivery, although a special fitting was supplied by the manufacturer to adapt the standard cannula to the DODS. We then plotted oxygen saturation vs minute oxygen supply curves for the DODS and steady flow during both exercise trials. The oxygen savings afforded by the DODS as compared to steady flow was then calculated. The oxygen per minute required to achieve 90 percent saturation using each delivery method was calculated, then the DODS minute oxygen usage was divided by the steady flow minute oxygen usage. The performance of the two delivery methods was compared statistically using paired t-tests to determine if a significant difference existed between the oxygen supply requirements of the DODS and steady flow to achieve 90 percent oxygen saturation.

RESULTS

Mean room air oxygen saturation was not significantly different for each delivery method. The mean respiratory rates were 16.2 ± 4.0 at rest and 19.5 ± 5.1 at the end of exercise. Oxygen saturation and the amount of oxygen required to produce adequate saturation each minute for all subjects, from each trial, using both oxygen delivery techniques, are shown in Table 2. All saturation readings were recorded at the end of the three minute exercise session. In most cases, both steady flow and the DODS were able to provide the subjects with enough oxygen to meet their physiologic needs during low-level exercise. However, much more oxygen was required using steady flow delivery than the DODS to achieve adequate oxygen saturation.

The performance curves of steady flow and DODS oxygen delivery are shown in Figure 2. At 90 percent saturation, the oxygen supply requirement was 211.4 ml/min for the DODS as contrasted to steady flow which was 1,610.9 ml/min. Therefore, the mean oxygen savings benefit of the DODS over steady flow delivery is 7.6:1 with a range of 3.9:1 (subject 6) to better than 10:1 (subject 3). These differences are statistically significant (p<.0001).

A comparison of oxygen utilization at 90 percent saturation for each delivery method is shown in Figure 3. Again, substantially more oxygen is required using steady flow delivery, as opposed to DODS delivery, to achieve equivalent oxygen saturation.

DISCUSSION

This study demonstrates that the demand oxygen delivery system can provide adequate oxygenation at a substantially reduced supply during exercise conditions. The oxygen savings using the DODS as compared to steady flow delivery is greater than 7 to 1. These results are consistent with the findings of our earlier study which demonstrated a comparable 7 to 1 savings during resting conditions. The fact that the oxygen savings using the DODS extends to exercise conditions lends support to its use in portable oxygen therapy.

One of the important areas of oxygen therapy, particularly in the home, is portable oxygen therapy. Many of the major problems encountered in oxygen therapy appear to be magnified in portable oxygen therapy. The weight, bulk, appearance, comfort and cost of oxygen therapy take on increasing importance. If less oxygen is required, then the oxygen storage cannister, which the patient must carry, can be less bulky and weigh less. While portable systems, both gas and liquid, are designed to be carried over the shoulders, patients with chronic lung disease are often too weak and debilitated to carry their oxygen and therefore require the aid of a wheeled cart. These carts increase the weight and decrease the maneuverability of portable oxygen, particularly when the patient must drive. A reduction in oxygen supply needs to the previous requirement could help increase the range of the present systems and reduce the necessary size of the oxygen cannister, thus permitting an increased range of activity.

An important benefit of oxygen conservation is the cost savings afforded by the reduction in oxygen usage over a given time, as shown in Figure 3. A patient who requires 2 L/min of continuous oxygen and is using compressed gas at home will require 12.5 K-cylinders...
at $30.00 per cylinder each month, (typical for the Los Angeles area). The total monthly charge is $375.00. If that same patient could be treated adequately with \( \frac{1}{2} \) as much oxygen, the number of oxygen cylinders per month could be reduced to 1.8. The cost of oxygen would be $54.00. However, the DODS could rent for as much as $50.00 per month which would bring the monthly charge for oxygen to $104.00. Thus, the actual savings would be $271.00 per month, or the proportionate benefit would be 3.6:1 over steady flow. That patient, under portable conditions, would be using compressed gas cylinders. The popular E-cylinder exchanges for about $16.00 per cylinder and lasts about five hours at 2 L/min of steady flow delivery or 35 hours via the DODS.

Liquid oxygen is often more expensive than compressed gas and there are several factors to consider when making cost comparisons. The DODS is designed to operate using liquid oxygen systems with oxygen savings similar to compressed gas delivery.

Patients using oxygen concentrators have no need for oxygen-conserving devices while on low-flow stationary oxygen. However, when such patients use portable oxygen, they usually have backup E-cylinders. If these patients use 14 cylinders per month at $16.00 per cylinder, the cost for the portable oxygen alone would be $224.00. This would have a negative impact on the use of the oxygen concentrator. With the DODS, only two E-cylinders would be required per month which would reduce the cost of portable oxygen to $32.00. Adding the DODS monthly rental charge of $50.00, the cost of portable oxygen in these patients would be $82.00 which improves the financial viability of the combination oxygen concentrator and portable compressed gas cylinders.

With the advent of increased public awareness and scrutiny of health care costs, such a reduction in oxygen requirement should be welcome. The average, per patient, cost of home oxygen is about $350 per month. \(^{31,37}\) When that cost by is multiplied by an estimated 300,000 patients on home oxygen, the cost is $105 million per month or $1.26 billion per year. While there are some fixed costs, the use of oxygen-conserving devices and techniques might make it possible to reduce the cost of oxygen therapy to 30-40 percent of the present level.

The fact that the DODS can provide substantial savings in oxygen utilization as compared to steady flow delivery is predictable. Steady flow oxygen is delivered throughout the respiratory cycle even though a majority of the cycle is spent in exhalation and a substantial portion of inhalation is spent in filling the deadspace. \(^{38}\) Thus, an estimated 20 percent of the original steady flow oxygen would be expected to contribute to the overall oxygenation of the patient's blood. Therefore, in order to maximize the efficiency of oxygen delivery, a reasonable goal is to direct all oxygen delivery exclusively to the earliest part of inhalation so as to avoid wasting oxygen.

An additional factor favoring early inspiratory oxygen delivery in the emphysema patient is the concept of fast space vs slow space ventilation. \(^{37,39}\) The fast space, according to the concept, fills during the earliest part of inhalation and is well perfused with pulmonary circulation. In contrast, the slow space, being last to fill, is also poorly perfused. Early inspiratory oxygen delivery would favor filling the fast space, thus providing more efficient arterial oxygenation. This effect would vary depending upon the ventilation/perfusion matching of the individual patient.

With the DODS, the volume of oxygen delivered is determined by altering the frequency with which breaths are supplemented with oxygen from the supply source. The frequency may vary from setting 1 which provides oxygen for only one of four consecutive breaths, to setting 4 during which each breath is supplemented. If a patient on setting 1 breathed 16 breaths per minute, that patient would receive only four oxygen delivery pulses per minute. Our observations did not reveal any disadvantages in intermittent oxygen delivery in the patient whose oxygen requirements were minimal. On the contrary, their oxygen saturations were equivalent to steady flow saturations at 1 L/min.

Methods of reducing oxygen usage, aside from electronic demand systems, are transtracheal\(^{38-40}\) and reservoir canulas. \(^{38-42}\) In both of these techniques, oxygen is introduced early in inspiration and oxygen can be conserved because of the lower supply flows necessary to accomplish adequate oxygen saturation. In the transtracheal method, \(^{38-40}\) oxygen is introduced directly into the trachea. Lower oxygen flows provide adequate oxygen saturation because oxygen is stored in the trachea toward the end of exhalation and substantial deadspace is bypassed. Oxygen savings between

**Figure 3.** Histogram comparison of the mean oxygen supply requirements of demand (DODS) and steady flow oxygen delivery required to achieve an oxygen saturation of 90%. Much less oxygen supply is required to achieve the oxygen saturation of 90% using DODS delivery (p<.0001).
2:1 and 3:1 have been reported. A significant advantage of transtracheal oxygen delivery is the fact that the delivery catheter can be hidden from view and thus may be more appealing cosmetically.

Reservoir cannulas save oxygen by storing it in a closely coupled reservoir during exhalation so that the stored oxygen, along with the continuous, but greatly reduced, supply oxygen, can be delivered during inhalation. There are two configurations of reservoir cannulas, one with the reservoir under the nose in the mustache region (Oxyzimer) and the other with the reservoir hanging on the front wall of the chest as a sort of pendant (Oxyzimer Pendant). Both reservoir cannulas accomplish oxygen savings of between 2:1 and 4:1 as compared to steady flow with the savings extending to exercise conditions. Long-term studies suggest that the reservoir cannula is reliable during extended use. The reservoir of the mustache-configured cannula is rather noticeable and some patients find it aesthetically displeasing. The reservoir of the pendant cannula is located on the anterior chest wall which alleviates some of the appearance problem, but is still noticeable.

Since the DODS maintains a high savings ratio during both rest and exercise, it is possible that smaller oxygen systems, lighter in weight and less bulky, could be developed which would further increase the portability and convenience of portable oxygen therapy. Moreover, since the DODS uses a standard steady flow nasal cannula, it does not suffer the cosmetic disadvantage of some of the reservoir cannulas.

Some oxygen-savings devices, particularly the reservoir cannulas, are in widespread use; transtracheal oxygen delivery is seeing greater use as well. Each oxygen conservation approach carries its own set of advantages and drawbacks. Since all of these methods are presently available and are used in patient care, we feel that the clinician should be aware of the advantages and disadvantages of each to best assist the patient in choosing the most appropriate alternative to meet their individual needs. For example, transtracheal delivery is least noticeable, but requires a surgical procedure; reservoir cannulas are the simplest and most reliable, but most noticeable as well; electronic demand systems are most efficacious; however, as mechanical systems are more complicated, one might expect mechanical failure or patient misuse would be more likely, although we had no such problem with our devices.

We conclude that the DODS can save substantial amounts of oxygen during not only resting conditions but exercise conditions as well, lending support to its use in portable oxygen therapy. This oxygen savings can be translated into significant cost savings and, perhaps equally important, the ability to improve the range and portability of oxygen therapy by allowing the use of smaller oxygen cannisters. Increased portability may contribute to improving the quality of life in patients requiring continuous oxygen therapy. We recommend long-term studies to confirm both the reliability and cost savings using the DODS.

ACKNOWLEDGMENT: We wish to acknowledge and thank Charles Adams, Oswaldo Be, M.D.; Jim Williams; and Gerri Dingler for their help and support in performance of the study and preparation of the manuscript.

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