
A Bench Study Comparison of Demand Oxygen Delivery Systems and Continuous Flow Oxygen

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BACKGROUND: Currently available methods for conserving oxygen include transtracheal catheters, reservoir cannulae, and demand oxygen delivery systems (DODS). DODS do not deliver oxygen during exhalation, and most models do not deliver oxygen during portions of the inspiratory cycle. To determine selected performance differences between DODS models and continuous flow oxygen (CFO), we conducted a bench model evaluation of 7 DODS models and CFO. **METHODS:** A bench model was constructed to simulate a nose, airway, and alveolar chamber. A linked ventilator drove the alveolar chamber to generate 3 respiratory patterns, at frequencies of 15, 20, and 26 per minute. DODS and CFO were tested at settings of 1, 2, 4, and 6 L/min. The fraction of inspired oxygen (F_{IO_2}) in the alveolar chamber was measured for each condition. Oxygen use efficiency (OUE) was calculated for each device by determining oxygen in the alveolar chamber/oxygen used by the device. **RESULTS:** The DODS models differed with regard to flow delivery profile. Supplemental oxygen (F_{IO_2} increase over 21%) for CFO declined markedly (43%) with increasing frequency, and was better maintained for the DODS models (average of 10% decrease). DODS that deliver an early inspiratory pulse tended to maintain F_{IO_2} with increases in frequency and to be more efficient with oxygen use. OUE was 21% for CFO, and ranged from 42% to 100% for DODS models. **CONCLUSIONS:** DODS models were not equivalent to CFO or to each other in F_{IO_2} or OUE. DODS conserve oxygen and may maintain F_{IO_2} better than CFO when respiratory frequency increases. DODS models differ and may require setting adjustments to achieve equivalent F_{IO_2} to CFO or to other models. To optimally customize oxygen therapy to the patient, the DODS model or CFO should be set to meet adequate saturation goals (ie, > 90%) under conditions of usual use, including rest and exercise. [Respir Care 1999;44(8):925-931] *Key words: demand oxygen delivery systems, continuous flow oxygen, oxygen use efficiency.*

Introduction

Although most oxygen therapy is administered as continuous flow oxygen (CFO), 3 methods of oxygen conservation have come into use. Transtracheal catheters deliver oxygen directly into the trachea, requiring approximately half the oxygen of a nasal cannula system to provide equivalent oxygen saturation.¹ Reservoir cannulae have a reservoir near the nose that fills with oxygen during exhalation,^{1,2}

and the reserved oxygen is inhaled at the onset of the next inhalation. A reduced flow setting thus conserves a significant amount of oxygen. Demand oxygen delivery systems (DODS) interrupt the flow of oxygen during exhalation, when the oxygen flow is otherwise mostly wasted. DODS either pulse oxygen early in inhalation or provide oxygen flow throughout inhalation. DODS use standard or modified nasal cannulae, and are set with "CFO equivalent" settings. The use-time of portable devices can then be extended, and/or smaller, lighter devices can be used. Transtracheal catheters and reservoir cannulae have found relatively low acceptance compared to DODS. First available in the 1980s, there were 18,000 DODS in use in 1994,² and approximately 80,000 units (industry estimate) were put into service in the United States in 1998.

The various DODS models interrupt exhalation-phase oxygen flow by different methods, thus producing different flow profiles. DODS flow is not the same as CFO, so controversy exists as to the "equivalence" of DODS and

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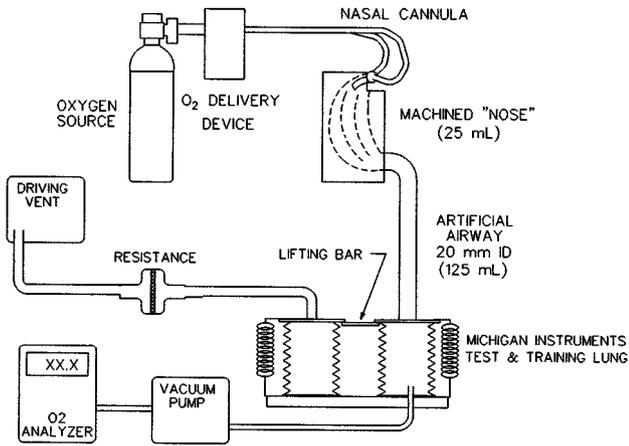


Fig. 1. Schematic of the demand oxygen delivery system/continuous flow oxygen (DODS/CFO) evaluation system. ID = internal diameter.

CFO settings. Each DODS manufacturer uses algorithms based on certain assumed breathing patterns to create CFO equivalent settings for their model. While DODS may function similarly to CFO under the assumed conditions, they may deviate from equivalence with other breathing patterns. Thus, clinical studies have shown DODS to produce similar results to CFO,^{1,3-6} but there are studies that report differences.⁷⁻¹⁰

Several difficulties are apparent in comparing DODS to CFO. The variability and lability in patients' breathing patterns make it difficult to control for and compare possible differences in oxygenation or exercise tolerance between DODS and CFO. Also, arterial oxygen saturation, which is often the outcome variable in comparison studies, shows small changes for large changes or differences in F_{IO_2} or arterial oxygen tension (P_{aO_2}). In studies comparing DODS with CFO, the initial CFO setting might be titrated with little or no effort to optimize it. It is possible that in studies in which oxygen savings over CFO were reported, a small reduction in the CFO prescription may have also realized oxygen savings without adverse effect on arterial oxygen saturation. Similarly, in studies that found DODS to be inferior to CFO at exercise, settings equivalent to CFO were used.⁷⁻¹⁰ It is possible that simply increasing the DODS setting would have created equal or better results while still saving oxygen.

Given the delivery differences between DODS and CFO, "equivalent" settings present difficulties in clinical comparisons. We devised a test lung model constructed to evaluate differences between DODS and CFO during three simulated breathing patterns. Differences found in a controlled setting, without anatomic, physiologic or other clinical variables, might help to explain clinical nonequivalence and might enable more knowledgeable setting of DODS to meet oxygenation goals and realize oxygen savings.

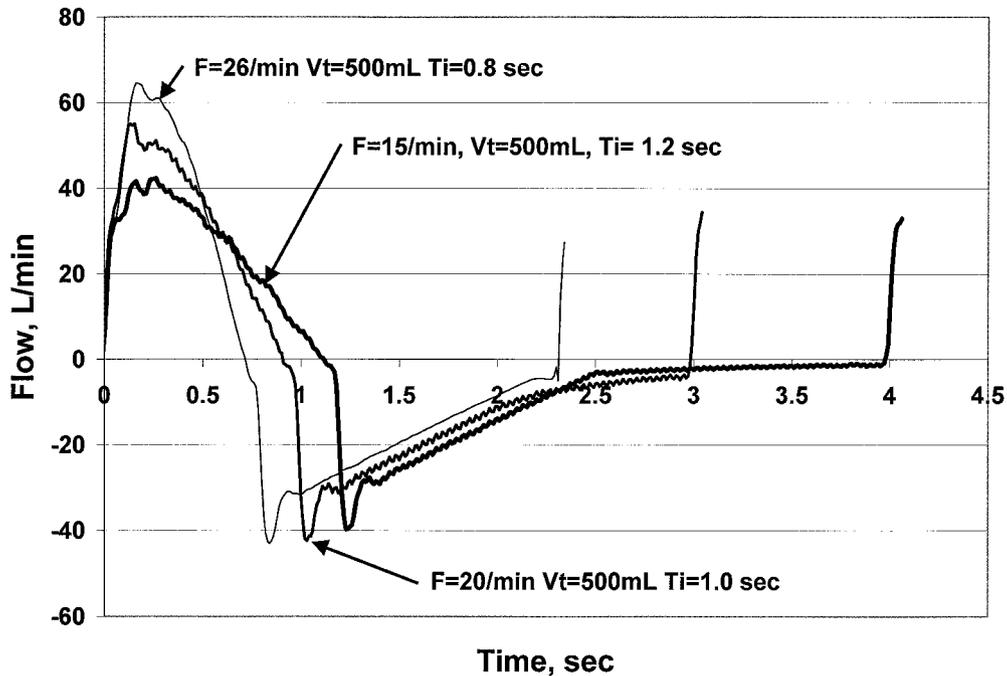


Fig. 2. Flow waveforms for low ($f = 15/\text{min}$), medium ($f = 20/\text{min}$), and high ($f = 26/\text{min}$) respiratory frequency breathing patterns. V_t = tidal volume. T_i = inspiratory time.

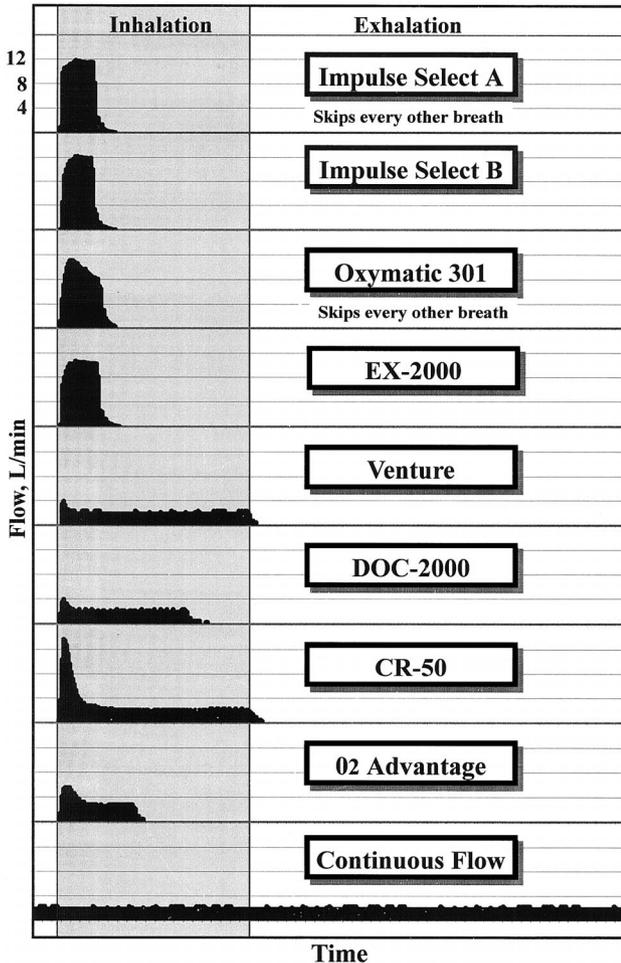


Fig. 3. Oxygen delivery flow profile for each demand oxygen delivery system (DODS) model, measured at a setting of 2, respiratory rate = 20/min, and inspiratory-expiratory ratio (I-E) = 1:2. The Impulse Select model DODS has 2 modes (A and B).

Equipment and Methods

Seven currently available DODS models (described in Appendix 1), and CFO, were evaluated using a mechanical lung model. The model was constructed to simulate a nose, conducting airways, and an alveolar chamber (Fig. 1). The conducting airways and nose represented a dead space volume of 150 mL. The apparatus was connected to a “respiring” limb of a test lung (Michigan Instruments, Grand Rapids, Michigan), driven by a linked ventilator (LP-6, Aequitron Medical, Plymouth, Minnesota). Three respiratory patterns were generated by the ventilator, representing low (f = 15/min), medium (f = 20/min), and high (f = 26/min) respiratory rate conditions, with tidal volume (V_T) = 500 mL, and inspiratory-expiratory ratio = 1:2 (Fig. 2). Prior to the F_{IO₂} testing, the oxygen flow profile output from the DODS models were measured by an electronic flow meter (model 4040, TSI Inc, St Paul,

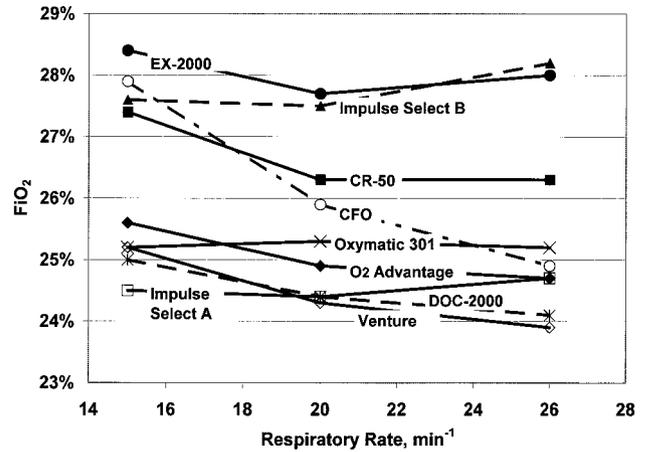


Fig. 4. Fraction of inspired oxygen (F_{IO₂}) measured for each demand oxygen delivery system (DODS) model and continuous flow oxygen (CFO) during the 3 breathing patterns shown in Fig. 2, as driven by the linked ventilator. Continuous flow oxygen (CFO) was set at 2 L/min, and the DODS models were set at 2.

Minnesota). Oxygen used was also measured by integrating the flow, using the TSI flow meter. F_{IO₂} in the alveolar chamber was measured by an oxygen analyzer (model OM-25A, Ceramtec Inc, Salt Lake City, Utah) for each breathing pattern, at 1, 2, 4, and 6 L/min settings for each DODS and for CFO.

Since oxygen use and F_{IO₂} vary between devices, an oxygen use efficiency (OUE) calculation was developed to evaluate the ability of each DODS model to both deliver and conserve oxygen. The OUE considers the amount of supplemental oxygen in the alveolar chamber (as measured via F_{IO₂}) relative to the amount of oxygen used from the source.

$$OUE = \frac{\text{supplemental oxygen in test lung}}{\text{oxygen used from source}}$$

$$OUE = \frac{(F_{IO_2} - 0.21) \times (V_T - V_D) \times 1/0.79}{V_{O_2}}$$

Where V_T = tidal volume (mL), V_D = dead space volume (mL), V_{O₂} = oxygen used from source per breath (mL), and F_{IO₂} = oxygen concentration measured in test lung.

Appendix 2 shows the derivation of the OUE calculation. The overall OUE was calculated by averaging the values for each of the 3 breathing patterns and the settings of 1, 2, and 4 L/min (setting 6 was not included because not all models have setting 6).

Results

The oxygen delivery flow profiles are shown in Figure 3. There were clear differences in flow profiles between

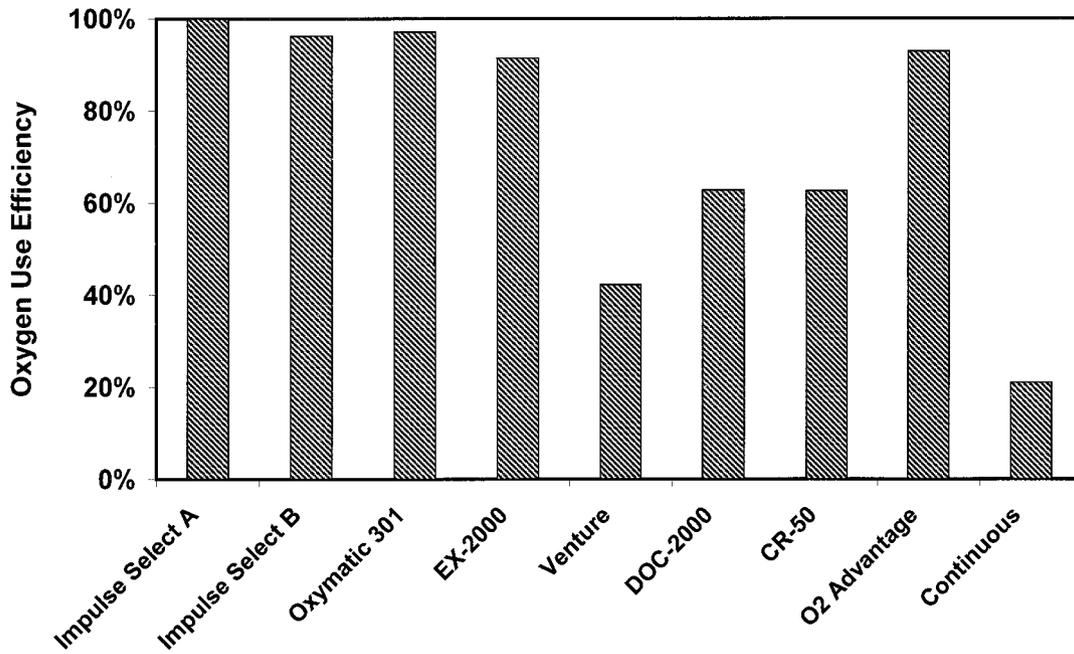


Fig. 5. Calculated oxygen use efficiency for 7 demand oxygen delivery system models and continuous flow oxygen.

DODS models; therefore, the models were identified as three types: pulse, demand and hybrid. The Impulse Select, Oxymatic 301, and EX-2000 models deliver an early inspiratory *pulse* of oxygen at a flow rate higher than the “equivalent” rate (setting in L/min). The Venture and DOC-2000 *demand* models deliver flow at the “equivalent” rate during most of the inhalation phase, as if in response to inspiratory demand. The CR-50 and O2 Advantage models are *hybrid* models with an early inspiratory pulse and a subsequent “equivalent” flow period.

Figure 4 shows the F_{IO_2} measurements for the 2 L/min setting. At settings of 1, 4, and 6 L/min, the devices displayed similar F_{IO_2} response to changing breathing patterns. There were differences between CFO and the DODS models in absolute values of F_{IO_2} and in patterns of response to increasing respiratory frequency. The F_{IO_2} values for CFO declined markedly with increasing frequency, while F_{IO_2} for the DODS models was maintained or declined slightly. Supplemental oxygen (F_{IO_2} increase over 21%) decreased 43% from low to high respiratory frequency for CFO. Pulse DODS models increased an average of 2%, demand models decreased 27%, and hybrid models decreased 18%.

Figure 5 shows the calculated OUE values. All of the DODS models tested provided more efficient oxygen delivery than CFO. The DODS displayed a wide range of efficiency values, and the pulse DODS models tended to achieve higher efficiency values than the demand or hybrid models.

Discussion

In this controlled-setting comparison of DODS models and CFO we found differences in absolute values of F_{IO_2} and patterns of response to increasing respiratory rate. Two previous studies comparing DODS models have found performance differences between models.^{8,10} We now report differences between models currently available that associate their flow delivery profiles with oxygen delivery and oxygen conservation. This can be explained by 3 factors: pooling, dilution, and timing of oxygen delivery.

Pooling

The higher F_{IO_2} delivered by CFO at the lower respiratory frequency can be explained by an anatomic reservoir, allowing pooling of oxygen from the end of the last exhalation. This pooling would occur if a potential chamber (nose) exists and end-expiratory flow from the patient has ended or is negligible. End-expiratory flow would flush the reservoir. In our model, as respiratory frequency increased, this effect diminished, since expiratory flow extends toward end-exhalation as expiratory time shortens. Demand type DODS delivered lower F_{IO_2} than CFO at low respiratory frequency, and nearly the same at high frequency. The pooling effect would explain this.

Dilution

With increasing respiratory frequency, the increase in minute ventilation dilutes the oxygen dose from CFO. The

pulse DODS models deliver the same volume of oxygen per breath regardless of frequency. This could explain the flatter F_{IO_2} response to increasing respiratory frequency with the pulse DODS models. Shortened inspiratory time might reduce dosing with the demand and hybrid models. The response of F_{IO_2} to increasing frequency is not as well maintained with the demand and hybrid models as with the pulse models.

Timing of Oxygen Delivery

The observed efficiency was also partly determined by the timing of the oxygen delivery. Assuming bulk gas flow, the final 30% of an inspiratory volume would occupy dead space (150 mL dead space, 500 mL V_T). If oxygen is delivered early in the inspiration, it is more likely to reach the alveoli, which would explain the higher efficiency of the early delivery pulse type DODS. Late inspiratory oxygen may just occupy proximal, dead space regions, so a demand type DODS that delivers oxygen during the later portion of inhalation would be less efficient than a pulse type, which delivers only during the early portion of inhalation. There are 2 hybrid devices: one that delivers throughout inhalation is less efficient than one that shortens delivery to a portion of inhalation. The differences in efficiency values are striking. The values imply that approximately 20% of the CFO reaches the alveolar chamber, while with some of the DODS models, almost 100% of the oxygen reaches the alveolar chamber.

There are several limitations of this bench study that suggest caution in extrapolating the findings to the clinical setting. First, this study does not account for the wide variability in breathing patterns. Only 3 breathing patterns were tested at 4 flow settings—hardly the full range of clinical use. The breathing patterns tested are not necessarily representative of other conditions such as sleep, vigorous exercise, or restrictive lung disease. For example, triggering-sensitivity of DODS may be an important issue when breathing is shallow. Device triggering sensitivity was not quantified in this study. Second, our lung model represents only some mechanical aspects of ventilation. Flow through a machined nose and smooth bore tubing may not produce the gas mixing characteristics of the human airway. Furthermore, the model cannot represent the distribution of oxygen throughout the lungs or its adsorption by the blood. Ventilation/perfusion relationships and gas distribution differ between patients and bear on oxygen delivery. Finally, since no oxygen was consumed in our setup, the actual F_{IO_2} measurements are artificially high and cannot be used for clinical comparison. Nevertheless, the model highlights differences between DODS

devices and CFO. It is clear that further investigation of DODS is necessary, particularly in the clinical setting.

Conclusions

As use of DODS spreads, a thorough understanding of their operation and appropriate application becomes increasingly important. In this bench study comparison of DODS models and CFO, we found differences that may be relevant to clinical practice. DODS models were not equivalent to CFO or to each other in F_{IO_2} delivery or OUE.

All 7 DODS models conserved oxygen (compared to CFO) and maintained a more constant F_{IO_2} with increasing respiratory frequency than did CFO. The pulse DODS models tended to conserve more oxygen and maintain a more constant F_{IO_2} than the demand and hybrid DODS models.

Further testing of DODS should include titration of settings under a range of conditions to attain adequate saturation while evaluating oxygen savings. To customize oxygen therapy to the patient, the DODS model or CFO should be set to meet adequate saturation goals (ie, > 90%) under conditions of usual use, including rest and exercise.

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Appendix 1

Devices Tested

Unless otherwise noted, all devices use a standard nasal cannula and operate on alkaline batteries.

Impulse Select. Airsep Corporation (www.airsep.com), Buffalo, New York. Airsep manufactures 2 demand oxygen delivery systems: the *Impulse* and the *Impulse Select*. We tested the *Impulse Select*. In operation mode A, the device operates similar to the CHAD *Oxymatic 301* (see below), delivering a 35 mL pulse at every breath when set at 4, skipping breaths at lower settings. At settings 5 and 6, the pulse is larger. In operation mode B, the device operates similar to the DeVilbiss *EX2000*, delivering fixed flow rate (12 L/min) pulses of longer duration with increasing setting. Includes built-in high pressure regulator for use with cylinder. The *Impulse* model operates similar to the CHAD *Oxymatic 301*.

Oxymatic 301. CHAD Therapeutics Inc (www.chadtherapeutics.com), Chatsworth, California. Delivers a fixed volume pulse (approximately 38 mL) of oxygen at the onset of inhalation. At setting 4, delivers every breath. At settings 3, 2, and 1, delivers on 3 of 4, every other, and every fourth breath, respectively. Uses any 20 psi oxygen source with a 4 L/min flow control.

EX-2000. DeVilbiss, a division of Sunrise Medical Inc (www.sunrisemedical.com), Somerset, Pennsylvania. Integrated high pressure regulator and conserving device that fits around the post valve of a high pressure cylinder. Delivers a pulse at 10 L/min at the onset of each inhalation. On time is varied from 0.050 to 0.6 seconds, depending on the setting. DeVilbiss also manufactures a liquid oxygen portable system with a similar demand oxygen delivery system built in.

Venture. Invacare Corporation (www.invacare.com), Elyria, Ohio. Connects to a standard fixed orifice regulator or liquid system. Delivers externally set "equivalent" flow rate for 1.0 seconds beginning at the onset of each inhalation. Rechargeable internal battery or AC adapter.

CR-50. Nellcor Puritan Bennett Corporation, a division of Mallinckrodt Inc (www.nellcorp.com), St Charles, Missouri. Integrated high pressure regulator, flow control and demand valve that mounts directly to a high pressure cylinder. Delivers a 12 mL bolus at the onset of each inhalation, then continues to deliver at the set flow rate (1–6 L/min) until the end of inhalation. Uses dual lumen cannula. Settings of 0.25, 0.50, and 0.75 L/min are automatically delivered in a continuous flow oxygen mode. Pneumatic (no battery). Nellcor Puritan Bennett also manufactures a liquid oxygen portable system with a similar demand oxygen delivery system built in.

DOC-2000. Transtracheal Systems (www.transtracheal.com), Englewood, Colorado. Connects to a standard fixed orifice regulator or liquid system. Delivers externally set "equivalent" flow rate for 0.7 seconds beginning at the onset of each inhalation. Similar in function to the Invacare *Venture*. *DOC-2000* is the only device that delivers continuous flow oxygen in the event of power failure, battery depletion, or apnea. Rechargeable, replaceable external battery or AC adapter.

O2 Advantage. Western Medica (www.westernmedica.com), Westlake, Ohio. Connects to a standard fixed orifice regulator or liquid system. Delivers a small bolus at the onset of inhalation and continues to flow at the externally set "equivalent" flow for a set portion of inhalation. Device can be set with internal switches to deliver for 33, 40, 50, or 70% of measured inspiratory time. Uses dual lumen cannula. Factory setting of 40% used in this study.

Appendix 2

Oxygen Use Efficiency Calculation

V_T	Tidal Volume (in mL)
V_D	Dead Space Volume (in mL)
V_{O_2}	Volume of Oxygen Used from Source (mL per Breath)
V_{O_2T}	Volume (in mL) of Oxygen Contained in Tidal Volume
V_{O_2L}	Volume of Oxygen Entering Alveolar Chamber (mL per Breath)
V_{AIR}	Volume of Air Entering Alveolar Chamber (mL per Breath)
F_{IO_2}	Fraction of Inspired Oxygen Measured

Define:

$$\text{Oxygen Use Efficiency} = V_{O_2L}/V_{O_2} \quad (1)$$

Mass balance assumptions:

$$V_T = V_{AIR} + V_{O_2L} + V_D \quad (2)$$

$$V_{O_2T} = V_T \times F_{IO_2} = 0.21 \times V_{AIR} + V_D \times F_{IO_2} + V_{O_2L} \quad (3)$$

Solve equation (3) for V_{O_2L} :

$$V_{O_2L} = V_T \times F_{IO_2} - 0.21 \times V_{AIR} - V_D \times F_{IO_2} \quad (4)$$

Solve (2) for V_{AIR} . Substitute into equation (4) and simplify:

$$V_{O_2L} = V_T \times F_{IO_2} - 0.21 \times (V_T - V_D - V_{O_2L}) - V_D \times F_{IO_2}$$

$$V_{O_2L} - 0.21 \times V_{O_2L} = (V_T - V_D) \times F_{IO_2} - 0.21 \times (V_T - V_D)$$

$$V_{O_2L} = (V_T - V_D) \times (F_{IO_2} - 0.21) \times 1/0.79 \quad (5)$$

Substitute equation (5) into equation (1):

$$\text{Oxygen Use Efficiency} = \frac{(V_T - V_D) \times (F_{IO_2} - 0.21) \times 1/0.79}{V_{O_2}}$$