Original Contributions

Characteristics of Demand Oxygen Delivery Systems: Maximum Output and Setting Recommendations

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BACKGROUND: Demand oxygen delivery systems (DODS) allot oxygen by interrupting the oxygen flow during exhalation, when it would mostly be wasted. Because DODS conserve oxygen by various methods, there are important performance differences between DODS. We studied certain performance factors that have not previously been carefully examined. METHODS: A bench model was constructed to simulate a nose, airway, and alveolar chamber. A breathing simulator generated 4 respiratory patterns, at frequencies of 15, 20, 25, and 30 breaths/min. Eighteen models of DODS were tested at 4 settings, each up to the maximum output, and compared to continuous-flow oxygen. The variable of interest was the fraction of inspired oxygen (F_{IO_2}) in the alveolar chamber, which was measured for each condition. RESULTS: The DODS differed from continuous-flow oxygen, delivering 0.5–2.1 times (mean = 1.13 times) the F_{IO_2} increase at similar settings. During maximum output the DODS showed a wide range of F_{IO_2}, from 0.27 to 0.46. There was a direct relationship between volume output per pulse in the first 0.6 s of inhalation and the delivered F_{IO_2}. CONCLUSIONS: DODS settings were not equivalent to continuous-flow oxygen in a bench model assessment; with equivalent settings the DODS tended to deliver greater F_{IO_2} than did continuous-flow oxygen. The maximum output capacity differed markedly among the DODS, and the user should know the device's capacity. A volume-referenced setting system for DODS should be adopted that would allow more predictable oxygen prescription and delivery via DODS. *Key words: oxygen, demand.* [Respir Care 2004;49(2):160–165. © 2004 Daedalus Enterprises]

Introduction

For over 4 decades, long-term oxygen therapy has been prescribed to treat chronic hypoxemia.[1,2] Demand oxygen delivery systems (DODS), which are designed to conserve oxygen, have been available for more than 20 years[3] but have realized widespread use in only the past 7 years. DODS allot oxygen by interrupting flow during exhalation, when the oxygen would mostly be wasted. DODs extend the use-time and/or decrease the weight of portable oxygen devices.

Pulse-type DODS deliver oxygen only early in inhalation. Demand-type DODS provide oxygen flow throughout inhalation.[4] Pulse-type DODS generally deliver a fixed volume of gas, at a relatively high flow that does not vary with changes in respiratory frequency. Demand-type DODS generally deliver a smaller bolus of gas at the onset of inhalation and then maintain a flow at or below the implied continuous-flow setting for the remainder of inhalation. DODS are labeled with seemingly arbitrary settings that imply equivalency to continuous-flow oxygen (CFO) prescriptions.

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Given the reported performance differences between DODS and CFO[4–7] we examined several factors to compare DODS to each other and to CFO. We devised a test-lung model system and designed a study to evaluate the fraction of inspired oxygen (F_{IO_2}) delivered under 16 simulated conditions. We speculated that differences found in a controlled setting (without anatomic, physiologic, or other clinical variables) might account for clinical non-equivalence. Differences found might enable more knowledgeable setting of DODS to meet oxygenation goals and

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Table 1.   Demand Oxygen Delivery Systems Tested

Model	Manufacturer	Type
CR 50	Puritan Bennett	Demand
Cypress 511	Chad Therapeutics	Pulse
EasyPulse	Precision Medical	Pulse
Escort	Penox Technologies	Pulse
EX2005	Sunrise Medical	Pulse
EX3000	Sunrise Medical	Pulse
Helios 300	Puritan Bennett	Demand
ImPulse Elite*	AirSep	Pulse
O2N Demand II	Victor Medical	Demand
O2Xpress	Salter Labs	Demand
OPC-830	Western Medica	Demand
OxyClip PC20	Puritan Bennett	Demand
Oxymatic 401A	Chad Therapeutics	Pulse
Oxymatic 411A	Chad Therapeutics	Pulse
Sequoia 302	Chad Therapeutics	Pulse
Sequoia 311	Chad Therapeutics	Pulse
Spirit 300	CAIRE	Pulse
Venture†	Invacare	Demand

*Has 2 modes. The "A" mode cuts the oxygen dose at a given setting in half relative to the
  "B" mode. Both modes were tested.
†Has several delivery modes. The factory setting of "variable" was used, in which the
  delivery time is a variable that changes with breathing frequency.

realize oxygen savings. In addition, since all DODS deliver a certain volume of oxygen per breath, we also examined the volume output of each DODS, as an approach to standardizing performance. Our goals, therefore, included an evaluation of the purported equivalence between settings, maximum output capacity, and the potential for a more accurate "volume-referenced" setting system.

Methods

The performance of 18 currently available DODS models (Table 1) and CFO were evaluated using a previously described mechanical lung model.[4] The test setup was constructed to simulate a nose, conducting airways, and an alveolar chamber. The conducting airways and nose had a dead space of 150 mL. The apparatus was connected to a spontaneous breathing simulator (Series 1100, Hans Rudolph, Kansas City, Missouri) that produced 4 respiratory patterns, at respiratory frequencies of 15, 20, 25 and 30 breaths/min, tidal volume of 500 mL, and an inspiratory-expiratory ratio of 1:2. Prior to the F_{IO_2} testing, the gas flow profile output from the DODS models was measured by an electronic flow meter (Model 4040, TSI Inc, St Paul, Minnesota). F_{IO_2} in the alveolar chamber was measured with an oxygen analyzer (Servomex, Sugar Land, Texas) for each breathing pattern at 1, 2, 4, and 6 L/min settings (as possible) for each DODS and CFO. With DODS that do not have settings of 5 or 6, all 4 settings were tested from 1 to the maximum.

A comparison ratio of DODS-to-CFO performance was calculated for each test condition. A ratio of 1 indicates equivalent F_{IO_2} measurements with the DODS and CFO, whereas a ratio of 2 would indicate that the DODS F_{IO_2} was twice that of CFO.

In addition, for each device and setting, oxygen delivery volume was measured by integrating the flow from the TSI flow meter. Further, the oxygen delivered in the first 0.6 s of inhalation at 20 breaths/min was calculated to allow interdevice performance comparison.

The coefficient of determination (r^2, calculated with commercially available software [Excel, Microsoft, Redmond, Washington]) was calculated to evaluate the strength of the associations between the DODS setting number and/or volume delivery and F_{IO_2}.

Results

Figure 1 compares the DODS measurements to the CFO measurements. There were differences in F_{IO_2} between CFO and the DODS models, and the DODS and CFO measurements were infrequently equivalent. F_{IO_2} delivery from DODS ranged from 0.5 to 2.1 times that of the purportedly equivalent CFO setting. Seventy-two percent of the measurements were not equivalent (ie, > 10% different). On average the F_{IO_2} from the DODS were 1.13 ± 0.34 times the CFO setting.

Figure 2 shows the maximum output of the DODS under the tested conditions. There was a wide range of performance among the devices. An intradevice comparison found a mean ± SD F_{IO_2} reduction of 0.053 ± 0.027 when respiratory frequency was increased from 15 to 30 breaths/min. At a maximum setting the range of F_{IO_2} at 15 breaths/min was 0.30–0.46, whereas at 30 breaths/min the F_{IO_2} range was 0.27–0.37.

Figure 3 shows the F_{IO_2} range of performance for all devices tested, at the various settings. Whereas F_{IO_2} delivery increased with increasing settings, the range of values between devices and conditions was wide at each setting: setting 1: 0.22–0.26; setting 2: 0.24–0.29, setting 3: 0.27–0.38; setting 6: 0.31–0.47 ($r^2 = 0.72$). A more linear relationship than the setting-based system was realized when the F_{IO_2} delivery was plotted against volume output by device type (Fig. 4), for both pulse-type ($r^2 = 0.76$) and demand-type ($r^2 = 0.84$) DODS. Furthermore, in a comparison of F_{IO_2} delivery within the first 0.6 s of inhalation the relationship was nearly direct (Figure 5) ($r^2 = 0.92$), with both pulse-type and demand-type DODS evaluated together.

Discussion

In this controlled-setting comparison of DODS models and CFO we found marked differences in F_{IO_2}. Previous studies
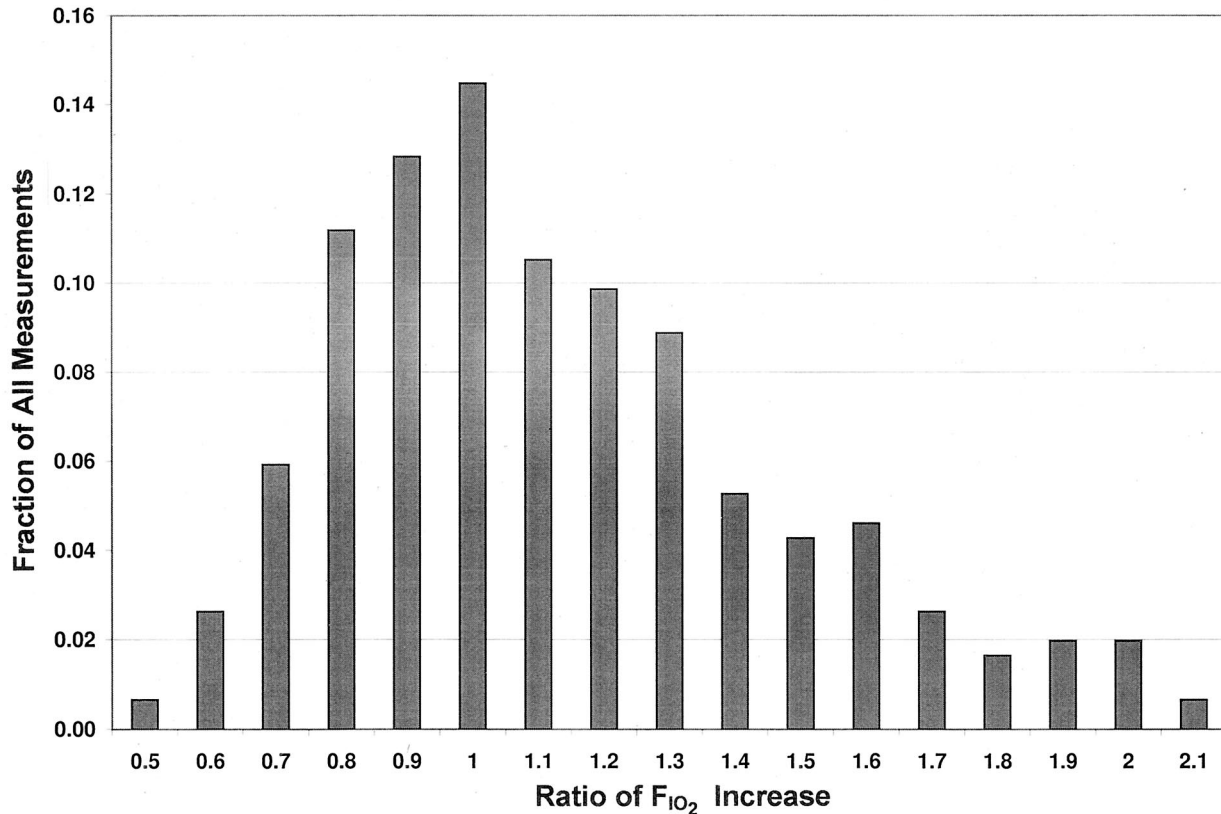
Fig. 1. Ratio of fraction of inspired oxygen (F_{IO_2}) increase with demand oxygen delivery systems (DODS) compared to continuous-flow oxygen (CFO), at the same DODS numerical setting. The ratio was calculated by the equation (DODS F_{IO_2} − 21%)/(CFO F_{IO_2} − 21%). Nearly equivalent oxygen delivery (ie, a ratio of 0.9–1.1) occurred in only 28% of the assessments. DODS oxygen delivery was as much as 2.1 times the CFO delivery, with an overall average of 1.13 times the CFO delivery.

comparing DODS models found performance differences between models.[4–7] In our previous study we proposed the effect of 3 factors (pooling, dilution, and timing[4]) to explain nonequivalence between devices, and we found that with CFO, increasing the respiratory rate decreased F_{IO_2}, whereas with DODS, increasing the respiratory rate caused less or no decrease. In the present study we examined other characteristics of DODS, conducted a more detailed comparison of purported equivalency between settings, studied the maximum output capabilities of devices, and evaluated volume-based settings. As previously discussed, there are several limitations of this bench study that suggest caution in extrapolating the findings to the clinical setting.[4]

Equivalency

The DODS settings were infrequently equivalent to CFO in the present study. The reasons for DODS/CFO nonequivalence have been previously discussed[4] (pooling, dilution, timing) and the present study provides further evidence of the extent of this problem. The DODS tended to deliver a lower F_{IO_2} (than did CFO) during low re-

spiratory frequency use and when using DODS models with low volume dose per numerical setting. DODS tended to deliver higher F_{IO_2} during high respiratory frequency use and when using DODS models with high volume dose per numerical setting. In either case, if the oxygen prescription is based on blood oxygen saturation measured via pulse oximetry (S_{pO_2}), the nonequivalence between devices is of lesser importance, since the setting is guided by S_{pO_2}. Prescriptions for a fixed-value setting for oxygen delivery do not allow for adjustments for the patient's range of activities or changing pulmonary status. The number and extent of setting adjustments could be reduced if DODS performance characteristics were better known by the user. The nonequivalence we found suggests that changing a patient to a different DODS (or to CFO) will require a complete reassessment of device settings to achieve S_{pO_2} goals.

Maximum Output

If properly titrated to achieve S_{pO_2} goals, the amount of oxygen delivered at a given numerical setting should not be a concern to the patient. If a certain S_{pO_2} value is the
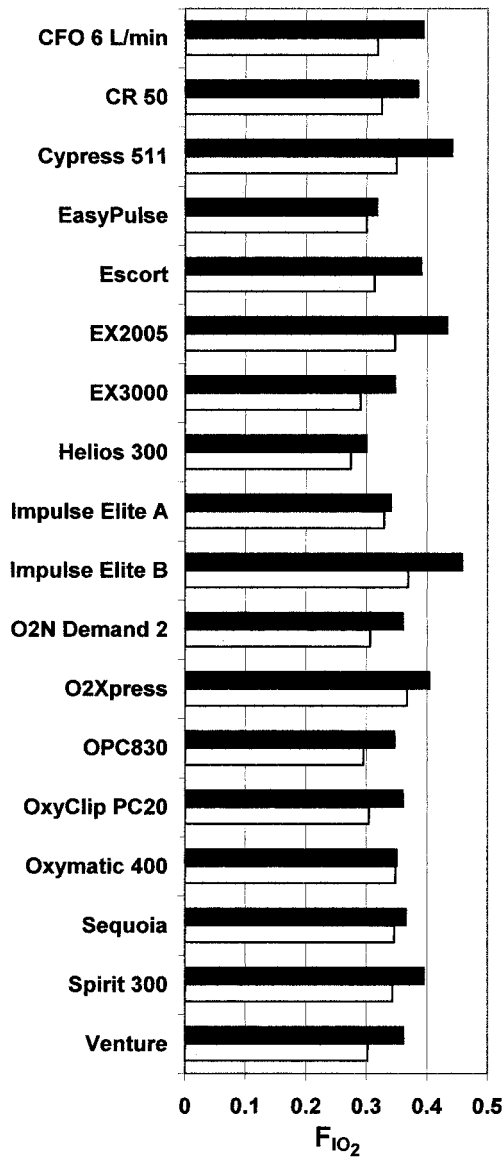
Fig. 2. Fraction of inspired oxygen (F_{IO_2}) at the maximum output setting with continuous-flow oxygen and the tested demand oxygen delivery systems. The black bars represent F_{IO_2} measurements taken at 15 breaths/min. The white bars represent F_{IO_2} measurements taken at 30 breaths/min. F_{IO_2} differed markedly among the devices at their maximum settings. The higher respiratory frequency reduced F_{IO_2} with all the devices tested. The Oxymatic 401 and 411 operate the same at their maximum settings, so only one entry is shown. The same is true for the Sequoia 302 and 311.

therapeutic goal, it doesn't matter if a setting of 2 is required on one device and 3 is required on another. What may distinguish performance limitations and differences between DODS models is the amount of oxygen available at the device's maximum setting. If the patient becomes dyspneic during exercise or during an exacerbation of his or her primary condition, it may be necessary to temporarily increase the oxygen flow, in which cases the de-

vice's maximum output may be needed to achieve the S_{pO_2} goal or to relieve dyspnea, and in some cases the maximum setting might not deliver enough oxygen to do that. Such oxygen delivery adjustments will require an assessment by the prescribing physician. We found marked differences between DODS in maximum output performance. The maximum output should be known by the user and the prescribing physician to assure that S_{pO_2} goals and dyspnea relief can be achieved. If the patient frequently uses the DODS at or near the maximum setting, a DODS with a greater maximum capacity may be required.

Volume-Referenced Setting

As expected, increasing the setting increased the F_{IO_2}. But, unfortunately, at a given numerical setting there is a disturbingly wide range of F_{IO_2} values among the DODS tested, and that range widens as the setting is increased. There are patient-related (ie, timing) and device-related (ie, algorithm, mechanical) explanations for those differences. For a concerned user and for the health care professional such uncertainty about oxygen delivery is troubling.

The problem of setting differences between DODS can be addressed by using a volume-referenced setting system that is based on the oxygen volume delivered per breath. Figure 4 shows that there is greater linearity in the F_{IO_2}/dose relationship with a volume-referenced setting system, especially at low dose volumes and respiratory frequencies. At higher dose volumes and respiratory frequencies the correlation is not as strong. This is probably due to the longer oxygen delivery duration and shorter inhalation time, which prevents some of the oxygen dose from entering the alveolar chamber, resulting in a lower-than-expected F_{IO_2} for a given dose volume.

Pulse-type devices generate a given F_{IO_2} at lower delivered volume than do demand-type devices. Demand-type devices deliver oxygen throughout inhalation, so some of the oxygen delivered late in inspiration does not reach the alveoli. Either device type will deliver a greater linear relationship with a volume-referenced setting system than with the current setting system.

The predictability of oxygen delivery can be further improved by modifying the volume-referenced criterion to consider only the volume delivered in the first 0.6 s of inhalation. Figure 5, based on this method, shows a very direct volume/F_{IO_2} relationship for both pulse-type and demand-type devices ($r^2 = 0.92$). A volume-referenced setting system would eliminate the somewhat arbitrary settings in current use, which falsely imply equivalence to CFO. Whereas we propose the adoption of standardized oxygen delivery settings, based on a bench model study, further investigations should be conducted in a clinical setting to evaluate a volume-referenced setting system that uses S_{pO_2} as an outcome.
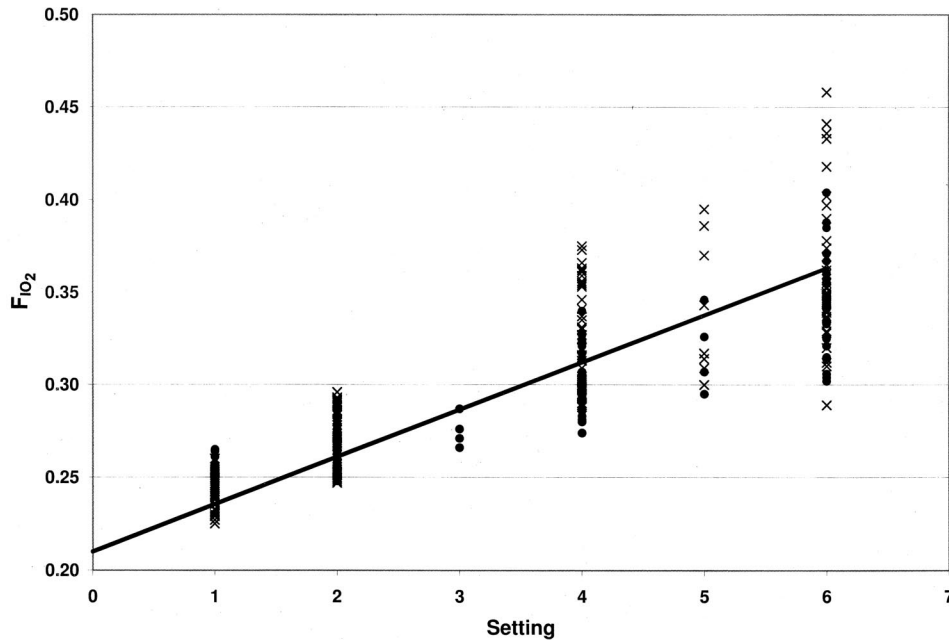
Fig. 3. Fraction of inspired oxygen (F_{IO_2}) delivered by all devices tested, at each available setting. Dots represent measurements from demand-type systems. Xs represent measurements from pulse-type systems. Among the systems tested there was a wide range of F_{IO_2} output at each setting ($r^2 = 0.72$), and that range widened as settings were increased.
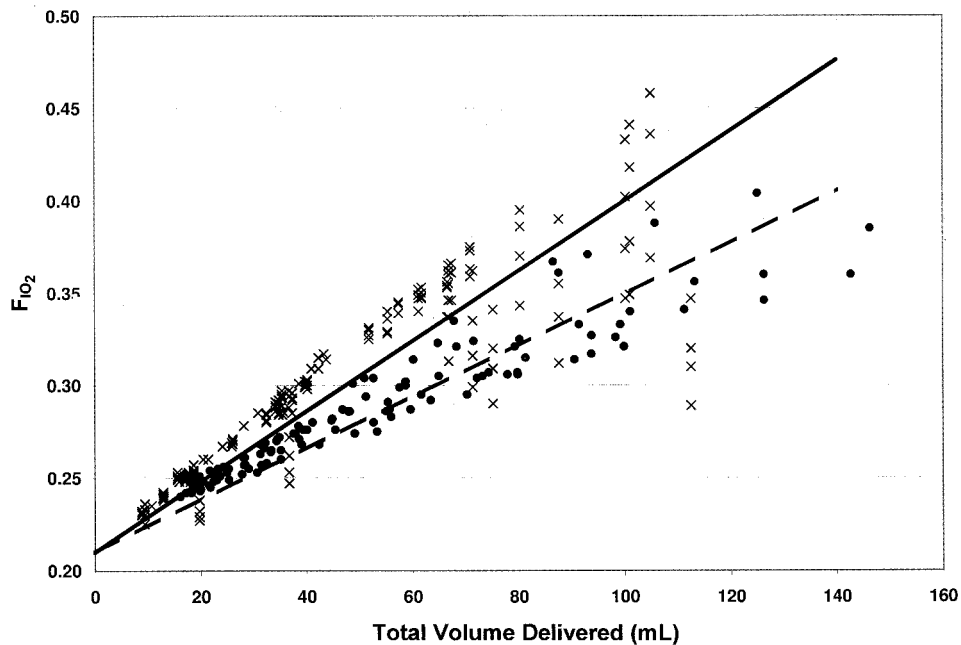

Fig. 4. Fraction of inspired oxygen (F_{IO_2}) as a function of the volume output of the oxygen delivery device. Dots represent measurements from demand-type systems. Xs represent measurements from pulse-type systems. The solid line represents the linear best fit for the pulse-type devices. The dashed line represents the linear best fit for the demand-type devices. The relationship between volume output and F_{IO_2} is more direct ($r^2 = 0.76$ for pulse-type and 0.84 for demand-type) with a volume-based system than with a setting-based system.

Conclusions

The DODS models we tested were not equivalent to CFO or to each other in F_{IO_2} delivery. DODS tended to deliver greater F_{IO_2} than the equivalent CFO setting. Whereas setting a DODS at its maximum output is not advisable, knowledge of the maximum output capability may be important under certain as-needed situations.
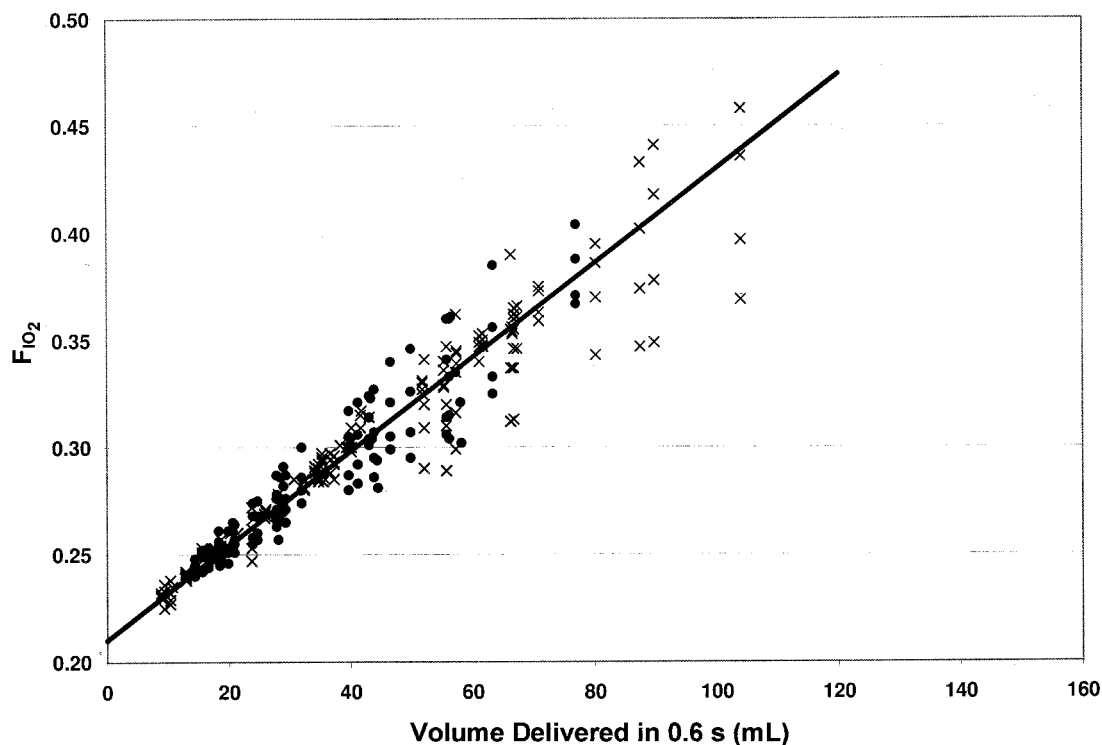
Fig. 5. Fraction of inspired oxygen (F_{IO_2}) delivered with a volume-based setting system, during the initial 0.6 s. Dots represent measurements from demand-type systems. Xs represent measurements from pulse-type systems. When volume output during the first 0.6 s is plotted against F_{IO_2}, the relationship is more direct ($r^2 = 0.92$) than the volume-based system (see Fig. 4) or the setting-based system (see Fig. 3), even with both pulse-type and demand-type models combined in the analysis.

We have reported the maximum output capacity of 18 available DODS and CFO. In light of the nonequivalence between devices, the DODS model or CFO should be set to provide adequate saturation ($> 90\%$) under conditions of usual use, including rest and exercise. Furthermore, a setting system should be adopted that is based on the volume of oxygen delivered by the device in use.

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