Shortcomings of Using Two Jet Nebulizers in Tandem with an Aerosol Face Mask for Optimal Oxygen Therapy*


Herein, a laboratory model which allows measurement of simulated distal airway oxygen percentage at different breathing patterns is described to illustrate the shortcomings of conventional O₂ devices and, in particular, the aerosol face mask with two jet nebulizers (AFM-DF) in tandem. A table showing the degree of dilution which occurred during simulation of various breathing patterns while using the AFM-DF is also presented. Data revealed that when 60 percent was desired, 13 of 27 measurements were less than 35 percent. The worst-case scenario for 60 percent desired was 45 percent measured. When 80 percent was desired, less than 70 percent was delivered in 24 of the 27 breathing patterns simulated. Less than 60 percent was measured on 12 occasions, with 51 percent being the lowest measurement. When 100 percent O₂ was desired, less than 80 percent was measured in 25 of 27 breathing patterns. Less than 60 percent was measured in ten of those. Fifty percent was the lowest analyzed value for the 100 percent setting. The inadequacy of AFM-DF is described in three case studies. A high-flow nonrebreathing face mask (HFM) to address the subset of patients is also discussed. A peak inspiratory flow prediction chart is also documented and may be useful in setting optimal flows when using high-flow systems. The patients in whom intubation and mechanical ventilation (or use of continuous mask CPAP) are indicated can be more clearly identified with a trial of high-flow O₂ therapy (with a system that assures adequate flow to meet the patient's peak inspiratory flow demands). In the remainder of patients, those higher-risk modalities will be precluded.

(Chest 1991; 99:1346-51)

AFM = aerosol face mask; AFM-DF = aerosol face mask double flow; HFM = high-flow nonrebreathing mask; I:E ratio = inspiration:expiration ratio; NR = nonrebreathing oxygen face mask; PIFR = peak inspiratory flow rate

The patient who manifests hyperventilation and hypoxemia due to any sort of cardiopulmonary insult presents an interesting challenge. Failure to improve the PaO₂ noninvasively may result in intubation and mechanical ventilation. Many times, the failure to show improvement with conventional oxygen devices is interpreted as a pure shunting problem, and further efforts to optimize O₂ therapy are aborted on that basis, with little consideration given to the possibility that the patient may have a high peak inspiratory flow demand which is diluting the alveolar O₂ percent considerably more than the clinicians at the bedside realize. When one considers that peak inspiratory flow rates measured in the pulmonary laboratory are often in the 100s of liters per minute, it is conceivable that conventional O₂ therapy devices will probably not be able to meet this demand. Even though most respiratory care textbooks state that the nonrebreathing oxygen face mask (NR) is optimal O₂ therapy for the spontaneously breathing nonintubated patient with refractory hypoxemia, it seldom fits well enough to achieve reliable alveolar O₂ concentrations. In recent years the aerosol face mask (AFM), with one or two jet nebulizers providing flow, has become a popular substitute for the NR. The potential advantages of simultaneously enhancing oxygenation and humidification, along with what appears to be a means of controlled O₂ therapy (the diluters are calibrated from 28 to 100 percent O₂) are certainly attractive. Unfortunately, the total gas flows which result at concentrations of 50 percent and above are not adequate to deliver the desired concentrations to the alveolar level of most adult patients. This report will attempt to clarify and quantitate that point.

The usual application of the aerosol face mask-double flow (AFM-DF) occurs when a patient presents in acute respiratory distress due to any number of cardiopulmonary insults (pulmonary edema, pulmonary embolus, pneumonia, early ARDS, etc), with a PaCO₂ in the 20s or low 30s and a PaO₂ less than about 50 mm Hg and a pH which is mildly to moderately elevated. Because of the aforementioned perceived advantages, an AFM at 40 or 50 percent would seem to be a reasonable O₂ prescription. If this does not result in an acceptable PaO₂, then the diluter on the nebulizer may be dialed up to 60 or 80 percent. If a short trial on an AFM fails to alleviate the problem,
then the patient is usually intubated and mechanically ventilated with PEEP. Mask CPAP would be advocated by many. The fact that the jets employed in these nebulizers only allow a maximum flow of about 12 to 14 L of 100 percent seems to be taken lightly. Although mask CPAP or mechanical ventilation with PEEP may be indicated in certain patients, some subtle observations suggest that optimization of flow should be accomplished before O₂ therapy attempts are abandoned. Close observation of the AFM exhalation ports by the astute clinician, while on the more tachypneic patients, would often reveal that aerosol (which serves as a tracer of the gas flow) would often be completely interrupted during much of the inspiratory phase of the spontaneous breath. This was interpreted to mean that the patient was preferentially pulling in room air. Many respiratory therapy departments have a policy to hang a second jet nebulizer and double the flow through the system at concentrations of 50 percent and above. This is better, but still susceptible to dilution by the peak inspiratory flow demands of many patients. The paradox with typical jet nebulizers is that at lower concentrations the total gas flow is high because of the high air entrainment ratios, but at higher concentrations the total gas flow deteriorates because less air is needed to achieve the higher concentrations; for instance, while using the 10-L/min setting on the flowmeter driving the nebulizer, at 28 percent the air-to-O₂ entrainment ratio is 10:1. The resultant total gas flow would be 110 L/min. At 35 percent the ratio is 5:1, so the total gas flow would be 60 L/min. At 40 percent the ratio is 3:1, so total gas flow would be 40 L/min. Up to this point the total gas flows are probably adequate for most patients, but as diluters are dialed to more closed positions, flow declines. At 60 percent the ratio is 1:1, so the total gas flow would be 20 L/min. At 80 percent the ratio is 1:0.3, so the total gas flow would be 13 L/min. At 100 percent, there is no air entrainment, so the total gas flow would be 10 L/min. Even if an attempt to turn the flowmeter up higher is made, 12 to 14 L seems to be the maximum flow that these jets will allow from a standard 50-psi outlet. Therefore, in centers where two jet nebulizers in tandem are used, maximum flows at 80 percent and 100 percent O₂ settings would be approximately 30 L/min and 24 L/min, respectively. The following bench study was an effort to quantitate approximately when and how much dilution occurs.

**Evaluation Methods**

In order to assess the dilutional effects of various breathing patterns, the simulation shown in Figure 1

![Diagram of a model for assessing the dilutional effects of different breathing patterns on the alveolar O₂ concentrations](image)

**Figure 1.** This device for assessing approximate distal airway O₂ concentrations originates with standard model intubation manikin with lungs removed. One main-stem bronchus is blocked off, while other is interfaced to TTL dual bellows test lung via standard corrugated tubing with ventilator circuit elbows (Inspiron) on both ends. Bellows are clamped together on TTL. Approximately 150 ml from main-stem bronchus, O₂ analyzer probe is placed in order to sample gas at what was believed to be simulated distal airway level. Frayser-Harlake respirometer was placed between the O₂ probe and bellows to measure actual delivered volume. Bellows with airway marked "to ventilator" is attached to a sine-wave-producing ventilator which is capable of generating any number of different breathing patterns. Part of the ventilator's set volume would be lost due to tubing compliance and gas compression. Adjusting volume upward slightly until desired value is measured on respirometer results in more accurate simulation. Then virtually any O₂ device may be placed on the intubation manikin's face; desired breathing pattern can then be generated with ventilator; and approximate alveolar concentrations may be read off analyzer.
was developed. This device for assessing approximate distal airway O₂ concentrations utilizes a standard model intubation manikin interfaced with a dual bellows test lung and a sine-wave-producing ventilator which is capable of generating any number of different breathing patterns. Virtually any O₂ device may be placed on the intubation manikin, and the device’s efficacy can be assessed at a number of breathing patterns. This simulation is a modified version of one Op’t Holt et al. used to assess demand valve resistance. After its development a preliminary study assessing the degree of dilution inherent in a number of O₂ delivery systems was undertaken. A RR of 30 breaths per minute and a V̇̇ of 800 ml with a sine wave ventilator set for a 1:2 I:E ratio was used for this first study. This was derived from the fact that a patient will tend to roughly double their resting tidal volume and then breathe faster when stressed. The following percentages were measured at the simulated distal airway level with the respective devices: simple face mask at 10 L/min, 38 percent; a 100 percent AFM at 10 L/min, 38 percent; a 60 percent AFM with two jet nebulizers in series and 10-L/min drive on each nebulizer for a total gas flow of 40 L/min, 40 percent; and a conventional NR at 12-L/min flow, 60 percent. Only the high-flow nonrebreather (HFM) depicted in Figure 2 achieved 100 percent. Later, with all other simulated parameters held constant, the V̇̇ was dropped to 600 ml, and a 100 percent AFM-DF with 12-L/min drive on each nebulizer was assessed. The

Figure 2. High-flow nonrebreathing face mask. This high-flow system originates from flowmeter or two capable of 100-L/min to 120-L/min flow (various brands of flowmeters are calibrated to 15 L/min, but capable of delivering anywhere from 50-L/min to 100-L/min flow when turned wide open). They may be plugged into a standard 50-psi wall outlet (if 100 percent O₂ is desired) or O₂ blender capable of flow of 100+ L/min. Standard O₂ connecting tubing conducts flow to inlet of low-resistance humidifier (Cascade, Concha, Vapophase, etc) via appropriate adaptors (Hudson one-way valves stacked, if necessary; Airlife adaptor 001507 or perhaps 001803 and 004081). From the humidifier outlet, O₂ travels through standard corrugated tubing to inlet of the reservoir bag (Airlife 001560, or Inspirons version suspended from IV pole). Depending on the humidifier, the temperature probe adaptor may be placed on an outlet port of the bag. Corrugated tubing would then conduct flow to a O₂ mask with flutter valves (B) over exhalation ports of mask (Salter SO-1). Small bag can be removed from conventional nonrebreather, and corrugated tubing will usually adapt well. Oxygen port will need to be capped. Flutter valve over inspiratory port (C) is optional (seems to stay blown open all the time anyway). During installation, the mask is held on the patient’s face snugly, and flow is titrated through humidifier until there is no noticeable collapse of the reservoir bag. It should appear distended at all times, with perhaps slight decrease in distention at the beginning of each inspiration. This assures that the patient’s inspiratory flow demands are being met. Any significant collapse tolerated while assuring that the mask is snug would translate into a source of air entrainment as soon as the mask’s fit became loose.
Table 1—Simulated Distal Airway O₂ Percent Using AFM-DF Set at 60, 80, and 100 Percent, Respectively*

<table>
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<tr>
<th>Vr, ml</th>
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*Values analyzed at simulated distal airway level of Figure 1. Ventilator (Puritan-Bennett 7200A) was attached to drive bellows and set to deliver respective Vr and rate settings in table. Flow was adjusted to deliver calculated peak flows from Table 2 while using sine wave flow pattern.

Simulated distal airway O₂ percent was only 56 percent. The results on the AFM-DF at 60 and 100 percent O₂ prompted further study to check the dilutional effects of various breathing patterns on the AFM-DF with the diluters set on 60, 80, and 100 percent. These data are recorded in Table 1, which combines all of the data into one table (with the exception of those measurements made at 40 breaths per minute to allow enlargement). Peak inspiratory flow rates for the respective breathing patterns appear in Table 2 and result from the following formula published in 1985 by Bar:¹²

\[
\text{PIFR} = \frac{\Pi VE (TI + TE)}{2TI}
\]

Notice in Table 1 that when 60 percent was desired, ten of 27 measurements were less than 55 percent. The worst-case scenario for 60 percent desired was 48 percent measured.

Also in Table 1, when 80 percent was desired, less than 70 percent was delivered in 20 of the 27 breathing patterns simulated. Less than 60 percent was measured on 12 occasions, with 53 percent being the lowest measurement.

Notice again in Table 1 that especially when 100 percent O₂ was desired, 91 percent was measured at the least demanding breathing pattern, which was a 200-ml Vr at a RR of 20 breaths per minute. Less than 80 percent was measured in 21 of 27 breathing patterns. Less than 60 percent was measured in eight of those. Fifty percent was the lowest analyzed value. Note, for instance, that at a Vr of only 400 ml and an RR of 20 breaths per minute, the analyzed value was 78 percent. If 100 percent is desired for alveolar-arterial gradient calculations, this 22 percent discrepancy would result in a mistake of over 100 mm Hg in the assumed PaO₂.

From a different perspective, the data in Table 1 illustrate what could happen when a patient at a given breathing pattern is increased to a higher concentration by simply dialing up the diluters on the nebulizers. Note in Table 1 that AFM-DF never achieved a 20 percent increase at the distal airway level, even though the changes made at the diluter were always 20 percent increases.

In fact, when the diluters were dialed from 60 percent to 80 percent, distal airway O₂ percent increases were less than 10 percent on 17 of 27 measurements (5 percent or less on 5 of the 17).

When diluters were dialed from 80 percent to 100 percent, distal airway O₂ percent increases were less than 10 percent on 21 of 27 comparisons (5 percent or less in 12 of the 21). On ten occasions the O₂ percent actually dropped when the diluter was dialed up from 80 to 100 percent.

When diluters were dialed from 60 percent to 100 percent, distal airway O₂ percent increases were less than 25 percent on 24 of 27 comparisons and less than 10 percent in 13 of those 24. In other words, the anticipated 40 percent increase in alveolar O₂ was actually 10 percent or less in half of the breathing patterns. This translates into a desired increase in PaO₂ of 200+ mm Hg, which actually approximates 50 mm Hg. One way to deliver the desired O₂ percent is to augment flow (see Fig 2). This methodology, when compared to other methods of delivering 100 percent O₂, resulted in PaO₂ increases averaging 121 mm Hg (16.1 kPa) in eight patients. Three are presented herein.

### Case Reports

**Case 1**

For three days after surgery, a stable postoperative cardiovascular patient had been receiving incentive spirometry and frequent IPPB and maintained a PaO₂ in the 80s on 24 L/min of 100 percent O₂ via two jet nebulizers in tandem and a modified nonrebreathing system. He was a rather large individual (198 cm [6 ft 6 in] and 113.4 kg...
Two Jet Nebulizers in Tandem with Aerosol Face Mask (Fouast et al)

[250 lb]), in whom the mask was not fitting optimally. On the fourth postoperative day, AM blood gas analysis revealed a pH of 7.44, PaO₂ of 85 mm Hg (11.3 kPa), and PaCO₂ of 37 mm Hg (4.9 kPa). Conversion to a HFM at approximately 60-L/min flow and 100 percent O₂ resulted in a pH of 7.42, PaO₂ of 275 mm Hg (36.7 kPa), and PaCO₂ of 39 mm Hg (5.2 kPa). The patient was decreased to 60 percent O₂ via an AFM with two jet nebulizers in tandem. The resultant PaO₂ was 72 mm Hg (9.6 kPa). Hence, this patient's degree and severity of hypoxemia was more clearly identified. Approximately 48 L/min of 60 percent O₂ was nearly comparable to 24 L/min of 100 percent O₂.

CASE 2

A tachypneic patient with end-stage hepatic disease and hepatic coma had the following blood gas levels on 24 L/min of 80 percent O₂ via two jet nebulizers in tandem and a modified nonrebreathing system: pH, 7.29; PaO₂, 53 mm Hg (7.1 kPa); and PaCO₂, 29 mm Hg (3.9 kPa). One hundred percent O₂ via an HFM at approximately 100 L/min revealed a pH of 7.31, PaO₂ of 303 mm Hg (40.4 kPa), and PaCO₂ of 26 mm Hg (3.5 kPa). The expected PaO₂, via a shunt chart should have been in the 60s. This marked improvement in PaO₂ after flow manipulation lends credence to the theory that a big part of the patient's problem was the dilutional effect of his breathing pattern on the lower O₂ flow.

CASE 3

A 40-year-old woman had undergone bowel repair surgery. One day after surgery, she was tachypneic, and blood gas analysis revealed a pH of 7.59, PaO₂ of 59 mm Hg (7.7 kPa), and PaCO₂ of 36 mm Hg (4.8 kPa) on an AFM at 40 percent O₂ via a standard jet nebulizer with 10-L/min drive on the Venturi jet, so total gas flow was 40 L/min. Oxygen percent was increased to 60 percent by dialing up the diluter. Blood gas levels 30 minutes later were a pH of 7.52, PaO₂ of 38 mm Hg (5.1 kPa), and PaCO₂ of 35 mm Hg (4.7 kPa). The gas flow was cut in half when the diluter was dialed up to 60 percent because the oxygen-to-air entrainment ratio changes from 1.3 to 1.1. The HFM was then initiated, and the resultant blood gas levels 30 minutes later were a pH of 7.43, PaO₂ of 340 mm Hg (45.3 kPa), and PaCO₂ of 43 mm Hg (5.7 kPa). This marked improvement could be attributed entirely to optimizing O₂ therapy so that no dilution could occur, or diureses of excess lung water or perhaps resolution of some atelectasis could have been contributing factors. What appeared to be a 30 percent shunt initially, which appeared to worsen to a 50 percent shunt, turned out to be a 15 to 20 percent shunt.

DISCUSSION

There are many ways to quantitate the degree of hypoxemia (alveolar-arterial gradients, percent shunt calculations, and PaO₂/FiO₂ ratios, to mention a few). Some authors use the latter to stage ARDS. One author states that hypoxemia should be considered refractory if the PaO₂ does not increase at least 10 mm Hg for a 20 percent increase in O₂ percent.1 He then suggests serious consideration be given to intubation and mechanical ventilation with PEEP. This is, of course, appropriate, assuming that the O₂ therapy employed produces reliably accurate alveolar concentrations on which to base the aforementioned O₂ challenge. Most conventional, unmodified, O₂ therapy devices, such as the AFM, do not.

Various forms of modified O₂ therapy have been discussed in the literature for years. The AFM-DF seems the most commonly used, although high-flow systems (Cascade/Concha type) are occasionally mentioned.5,13–15 These are usually open systems (large-bore tubing to an AFM) with arbitrarily selected flows. Anecdotal experiences or personal bias might lead one to presume that 40-L/min or perhaps 60-L/min flow would be adequate for virtually all spontaneously breathing patients. The data in Table 2 would suggest otherwise. These calculated peak inspiratory flows should approximate the needs of patients with the respective breathing patterns. These are mathematically symmetrical sine waves and may not be precise for a tachypneic patient, but certainly identify a minimum value with which to start. Three or four times the minute volume is often the recommended flow for these devices, but it is doubtful that VE is routinely measured in the acute setting. It appears that many times 40 L/min or less is considered adequate.

In summary, the data in Table 1 suggest that AFM-DF at 60 percent with a total gas flow of approximately 48 L/min is usually adequate; yet, when one considers that peak inspiratory flows measured in the pulmonary laboratory are several times this amount (5 to 9 L/s), it is conceivable that an acutely hyperventilating hypoxicemic individual may significantly exceed this output for a transient period of time. An AFM-DF at 80 percent is significantly inadequate and an AFM-DF at 100 percent is dangerously inadequate (delivering lower distal airway concentrations than 80 percent on 25 occasions). The high-flow system (Fig 2) did result in 100 percent O₂ delivery in the most diluted breathing pattern. It, therefore, would be capable of delivering 100 percent at the less demanding breathing patterns. This type of patient that presents with hypoxemia and hyperventilation concurrently would conceivably seem at particular risk for several reasons. The combined effects of hypoxemia, increased hemoglobin affinity for O₂, and cerebral vasocostriction may have a detrimental effect on the brain. The potential hypokalemia, secondary to the respiratory alkalosis, coupled with the aforementioned hypoxemia and increased hemoglobin affinity for O₂, could cause myocardial irritability. The tendency, in this setting, to initiate O₂ therapy with a conventional device that, in theory, delivers a medium to moderately high O₂ percent, allows for potential misinterpretation due to the inherently inadequate flows of conventional O₂ devices. If there happens to be a coexisting metabolic acidosis (partially or completely compensated), the potential for dilution may be even greater. If hardly any compensation exists, the patient may be on the verge of decompenating, and mechanical ventilation should be seriously considered. If the metabolic acidosis is secondary to distributive or cardiogenic shock, mechanical ventilation may also be

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indicated in order to minimize the respiratory muscle perfusion requirement.\textsuperscript{16}

The information presented in this article reveals that quantitating the degree of hypoxemia based on the response to conventional O\textsubscript{2} devices by calculating shunt or alveolar-arterial gradients or PaO\textsubscript{2}/FIO\textsubscript{2} is erroneous and could lead to unnecessary or premature intubation and mechanical ventilation or use of continuous mask CPAP in some patients. The patients in whom those modalities are indicated can be more clearly identified with a trial of high-flow O\textsubscript{2} therapy (with a system that assures adequate flow to meet the patient's peak inspiratory flow demands). The AFM, even with two jet nebulizers in series, is seldom adequate. Early intervention with an adequate flow of O\textsubscript{2} in these patients who are hyperventilating and hypoxic is paramount. Trials on lesser devices and waiting for blood gas results between each change of device only provides more time for fatigue to occur in a patient who otherwise might have been saved the morbidity of mechanical ventilation. Hypoxemia can easily be addressed by tapering back the O\textsubscript{2}. In theory, absorption atelectasis could confuse the picture, but a drop in PaO\textsubscript{2} in nine test cases was never noted. One patient had a PaO\textsubscript{2} of 56 mm Hg on 24 L/min of 100 percent O\textsubscript{2}, and her PaO\textsubscript{2} remained 56 mm Hg on 100 L/min of 100 percent O\textsubscript{2}. When high-flow manipulation is successful in correcting hypoxemia, the patient often responds by breathing significantly slower and may then be amenable to conventional O\textsubscript{2} therapy (which may be of particular interest to those readers in smaller institutions with a limited bulk O\textsubscript{2} supply). The convenience of having blenders mounted in such a way as to maintain the same high-flow system is relatively simple. Oxygen toxicity is of minimal concern because most patients require either mechanical ventilation or less than 60 percent O\textsubscript{2} within 24 hours.

In some cases, excessive (more labor intensive) pulmonary hygiene may be ordered to correct the perceived refractory hypoxemia which, in some cases, may be in part due to the patient's ability to dilute the flow of the device. Readers should be encouraged to adopt some form of modified O\textsubscript{2} therapy (capable of flows of 100+ L/min)\textsuperscript{14} to address this subset of patients. It seems likely that part of the success attributed to mask CPAP may be due to the fact that it is set up with a high-flow device, the Downs flow generator, which is capable of 100+ L/min.

In closing, there is a substantial difference in delivered O\textsubscript{2} percent with these genuine high-flow systems when compared to two jet nebulizers in tandem, so much so that this sort of flow manipulation should be considered first-line therapy (and standard operating procedure) for the early management of hyperventilating individuals with a suspected hypoxic insult. We would also suggest that manufacturers of jet nebulizers consider adding additional labeling or instructions to alert the user to the limitations at concentrations above 60 percent. At any rate, we would encourage the early implementation of a genuine high-flow system in hyperventilating hypoxic patients, in order to better quantitate the degree of hypoxemia and better guide subsequent therapeutic interventions.

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