Fraction of Inspired Oxygen Delivered by Elisée™ 350 Turbine Transport Ventilator With a Portable Oxygen Concentrator in an Austere Environment

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ABSTRACT

Background: Management of critically ill patients in austere environments is a logistic challenge. Availability of oxygen cylinders for the mechanically ventilated patient may be difficult in such a context. One solution is to use a ventilator able to function with an oxygen concentrator (OC). **Methods:** We tested two Elisée™ 350 ventilators paired with SeQual Integra 10-OM oxygen concentrators (OC) (Chart Industries, http://www.chartindustries.com) and evaluated the delivered fraction of inspired oxygen (FIO_2). Ventilators were connected to a test lung and FIO_2 was measured and indicated by the ventilator. Continuous oxygen was generated by the OC from 0.5L/min to 10L/min, and administered by the specific inlet port of the ventilator. Several combinations of ventilator settings were evaluated to determine the factors affecting the delivered FIO_2. **Results:** The Elisée 350 turbine ventilator is able to deliver a high FIO_2 when functioning with an OC. However, modifications of the ventilator settings such as an increase in minute ventilation, inspiratory-to-expiratory ratio, and positive end-expiratory pressure affect delivered FIO_2 despite steady-state oxygen flow from the concentrator. **Conclusion:** OCs provide an alternative to oxygen cylinders for delivering high FIO_2 with a turbine ventilator. Nevertheless, FIO_2 must be monitored continuously, since it decreases when minute ventilation is increased.

Keywords: *mechanical ventilation; oxygen delivery; oxygen, low-flow; oxygen concentrator; Elisée™ 350*

Introduction

Mechanical ventilators commonly use a high-pressure oxygen source for oxygen delivery; however, availability of this resource can be challenging in austere environments. High-pressure oxygen is standard and required for precise control of the fraction of inspired oxygen concentration (FIO_2) during mechanical ventilation. Compressed oxygen is not always available early in military deployments or during disaster response.

The French Army is often engaged in overseas operations in remote or austere environments such as Afghanistan and Africa. Providing medical support to these operations is challenging because of the significant distance from France and lack of reliable medical resources locally. The French Military Health Service (FMHS) has gained notable experience in these environments. Its guiding principles are frontline medical care, frontline resuscitation and surgical care, and early secondary medical evacuations. One strategy the FMHS uses to achieve these is the forward surgical unit (FSU), comprising a light, mobile structure consisting of six tents with their own electrical power and a team of one general surgeon, one orthopedic surgeon, one anesthesiologist, and nine nurses. The FSU permits anesthesia, intensive care, and damage control surgery closer to the point of injury. The surgical team is capable of performing 10 operations per day during a 2- to 4-day period.[1] Recently, a vital surgery unit (VSU) has been developed and made available to Special Forces.[2] The VSU is manned by one general surgeon, one anesthesiologist, and two nurses, and incorporates a very light, mobile structure (1,000kg; 4m^3). This unit can be deployed under a tent, on a surface ship, or directly in a tactical transport aircraft.

The contexts in which these structures operate require mobility of their equipment and make the oxygen supply hazardous and difficult to support. The use of cumbersome oxygen production modules is not possible in such settings. FSUs and VSUs are equipped with limited stocks of oxygen cylinders, which might be quickly exhausted in case of massive combat casualties; thus, portable oxygen concentrators (OC) have been proposed as a solution for mobile oxygen production.[3] Furthermore, medical oxygen is in limited supply in the developing world. As such, OCs have been proposed as a suitable option in Africa[4] and in mountainous environments.[5] However, the literature on mechanical ventilation with an OC is lacking, especially on reliability of delivered FIO_2 with this oxygen source. Two studies focused on the delivered FIO_2 when a ventilator was coupled with an OC.[6,7] Rodriquez et al.[6] described the use of a portable

OC modified to provide pulse dosing on inspiration and maximize oxygen delivery, but this method is not a routine use of OC. Bordes et al.[7] tested an old transport ventilator, LTV 1000 (CareFusion Corp.; http://www.carefusion.com), to determine FIO_2 delivered with OC. The Resmed Elisée™ 350 (http://www.resmed.com) is a recently developed, portable ventilator with an internal turbine that is not dependent on a high-pressure driving gas supply. Low-pressure oxygen is inserted at a specific port on the rear of the device. This new ventilator has been chosen by the FMHS to equip the FSUs. However, to our knowledge, the capacity of this ventilator to deliver FIO_2 when functioning with an OC has never been published. The aim of this study was to measure the FIO_2 achievable when the Elisée 350 was used with an OC as the only source of oxygen.

Materials and Methods

This study was performed in the French military FSU in Niamey, Niger, in January 2015. This FSU has been in place for 1 year. All measurements were obtained in the intensive care tent at a temperature of 25°C (77°F) in an environmentally controlled room.

The Elisée 350 ventilator was the ventilator used for this study (Table 1). Oxygen was delivered by a SeQual Integra 10-OM OC (Chart Industries, http://www.chartindustries.com). The Elisée 350 ventilator and SeQual Integra 10-OM OC were selected because they are used by the FMHS in FSUs. The SeQual Integra 10-OM OC is capable of generating from 0.5 to 10L/min of continuous oxygen flow. It is an electronically operated OC that separates oxygen from ambient air. This OC is equipped with an oxygen monitor that provides continuous monitoring of oxygen concentration. An indicator light is activated when oxygen concentration falls below preset levels (85% and 70%). This OC delivers FIO_2 above 90% at any oxygen flow.[7]

Experimental Setup

We tested two Elisée 350 ventilators coupled with two OCs (Figure 1). They were used on alternating-current mode. Low-pressure oxygen was supplemented at the specific port on the rear of the ventilator and supplied from the OC at a flow of 0.5–10L/min.

Table 1 *Elisée 350 ResMed Ventilator and SeQual Integra 10-OM OC Specifications*

Elisée 350 ResMed ventilator specifications	
Weight (kg)	4.5
Dimensions (mm)	290 × 250 × 130
Breath types	Volume control, pressure control, pressure support, spontaneous
Tidal volume range (mL)	20–2,500
PEEP range (cmH_2O)	0–25
Breath rate (breaths/min)	2–50
Operating environment guidelines	
Temperature range	5°C–40°C
Relative humidity range	10%– 95%
SeQual Integra 10 OM OC specifications	
Dimensions (inches)	26.5 × 14.7 × 19.5
Rate flow (L/min)	0.5–10
Outlet pressure oxygen, psi (KPa)	Nominal 6.0 (41.4)
Operating environment guidelines	
Temperature	10°C–40°C
Relative humidity	10%–95%

OC = oxygen concentrator; PEEP = positive end-expiratory pressure.

Ventilators were connected to a 3L test balloon (SilkoBag Rush; Teleflex Medical; http://www.teleflex.com) and a Hydro-Guard Mini heat and moisture exchanger (Intersurgical; http://www.intersurgical.com) via the manufacturer-supplied circuit. We used the analyzer integrated in the ventilator to continuously measure FIO_2.

Elisée 350 ventilators were in volume control. Table 2 details the different combinations tested.

Figure 1 **(A)** *Intensive care bed in the French military forward surgical unit.* **(B)** *Bench test.* **(C)** *Port for low-flow oxygen source on the rear of the ventilator.* **(D)** *SeQual Integra 10-OM oxygen concentrator.*

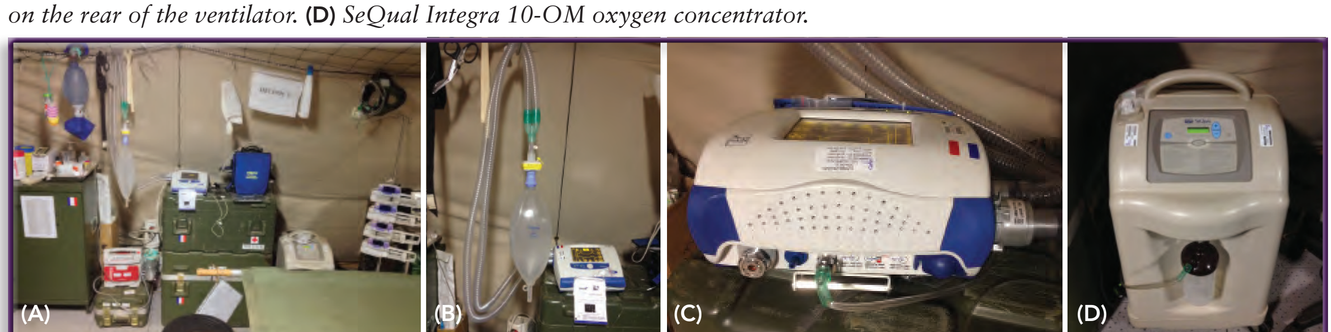


Table 2 *Elisée 350 Ventilator OC Parameters in Tested Combinations*

Ventilators Settings	OC Oxygen Flow (L/min)	I/E Ratio	Tidal Volume (mL)	Respiratory Rate (rate per min)	PEEP (cmH_2O)
Respiratory rate	0.5, 1, 2, 3,4, 5, 6, 7, 8, 9, 10	1:2	500	8, 10, 12, 14, 16, 18, 20, 26	0
I/E ratio	2, 4, 8	1:1, 1:2, 1:4, 1:9	500	12	0
PEEP	2, 8	1:2	500	12	0, 5, 10, 15

I/E = inspiratory-to-expiratory ratio; OC = oxygen concentrator; PEEP = positive end-expiratory pressure.

Measurements

FIO_2 breath-to-breath measurements were made. A period of 10 cycles was allowed for stabilization at each setting. FIO_2 at each ventilator setting was measured three consecutive times with both ventilators. All measurements were repeated with a second OC.

The difference in FIO_2 delivered by the two ventilators was less than 10% at each setting. Therefore, the values were averaged for analysis.

Statistical Analysis

FIO_2 values are expressed as mean ± standard deviation (SD). Comparisons between delivered FIO_2 at a given OC oxygen flow and ventilator parameters were compared by using a Student *t* test. An analysis of covariance was used to determine factors independently affecting delivered FIO_2. All analyses were performed with SPSS 20.0 (IBM Corp.; http://www-01.ibm.com); *p*-values less than .05 were considered statistically significant.

Results

A total of 1,200 measurements were performed. There was less than 5% difference in FIO_2 delivered by the two ventilators or OC at each OC oxygen flow tested with same positive end-expiratory pressure (PEEP), inspiratory-to-expiratory ratio (I/E), and minute ventilation. FIO_2 delivered by Elisée 350 ventilators without oxygen supplementation was measured at 21%.

FIO_2 Delivered by Elisée 350 Operating With an OC

The FIO_2 delivered by the Elisée 350 ranged from a minimum of 21% to a maximum of 89% when the ventilator operated with an OC oxygen source from 0.5L/min to 10L/min (Table 3, Figure 2).

Effects of OC Flow on Delivered FIO_2

Increase in OC oxygen flow led to an increase in delivered FIO_2 when minute ventilation remained constant (Table 3, Figure 2). At a constant minute ventilation of 6L/min (500mL; rate, 12), delivered FIO_2 ranged from 22.8% at OC flow of 0.5L/min to 79.3% at OC flow of 10L/min.

Effects of Respiratory Rate on Delivered FIO_2

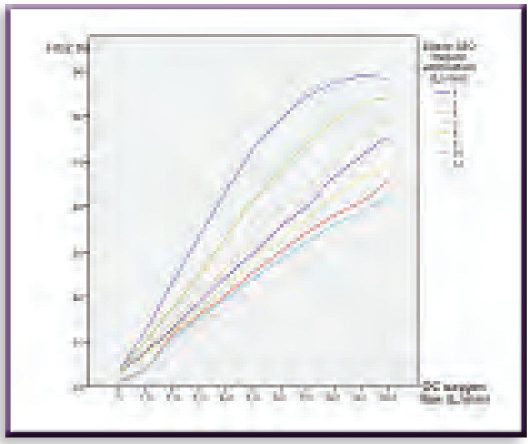
Increasing respiratory rate, when tidal volume and OC oxygen flow remained constant, reduced delivered FIO_2 (Table 3, Figure 2). As a result, increase in minute ventilation resulted in decreased delivered FIO_2. At a constant OC flow of 10L/min, delivered FIO_2 decreased from 88.5% at a minute ventilation of 4L/min to 56.8% at a minute ventilation of 13L/min.

Table 3 *Delivered Fraction of Inspired Oxygen in Various Minute Ventilation and OC Flow Conditions*

	Minute Volume (L/min)							
OC Flow (L/min)	4	5	6	7	8	9	10	13
0.5	23.5	23.5	22.8	23.0	23.0	21.3	21.0	21.0
1	32.7	30.3	28.3	28.0	27.3	24.0	24.0	23.0
2	43.3	37.7	35.0	33.0	32.5	31.8	31.0	30.0
3	53.5	44.8	41.0	38.8	37.3	36.0	35.3	33.5
4	63.5	53.5	47.3	44.5	42.5	40.5	39.8	37.8
5	72.8	61.3	53.8	49.8	48.0	45.5	44.0	41.0
6	79.3	68.3	59.5	55.5	53.0	50.0	48.0	44.3
7	84.5	74.0	65.0	60.0	57.3	54.3	52.3	48.0
8	87.3	79.0	70.0	66.5	62.0	58.0	56.0	51.0
9	89.0	82.8	75.0	71.0	66.3	60.8	58.5	53.0
10	88.5	84.3	79.3	75.5	69.0	65.5	62.3	56.8

FIO_2 = fraction of inspired oxygen; OC = oxygen concentrator.

Figure 2 *Delivered fraction of inspired oxygen (F_{IO_2}) according to oxygen concentrator (OC) oxygen flow chart.*



Effects of I/E Ratio on Delivered F_{IO_2}

There was a statistically significant difference in F_{IO_2} when the expiratory time was modified to I/E = 1/2 (Table 4) when all the other parameters remained constant.

Effects of PEEP on Delivered F_{IO_2}

There was statistically significant difference between the delivered F_{IO_2} at 0, 10, and 15cmH$_2$O of PEEP when all the other parameters remained constant (Table 4).

Factors Affecting the Delivered F_{IO_2}

The factors that independently affected the delivered F_{IO_2} were OC flow, minute ventilation, I/E, and PEEP (Table 5).

Discussion

In this study, we showed the Elisée 350 ventilator is able to deliver high F_{IO_2} with an OC tested in a resource-limited surgical unit setting. However, modifications of the ventilator settings may significantly affect the delivered F_{IO_2}. This study provides useful clinical performance data for the Elisée ventilator when paired with the SeQual Integra 10-OM OC for use in mechanical ventilation in austere locations.

Table 4 *Effects of I/E Ratio and PEEP on Delivered F_{IO_2}*

Parameter	OC Flow (L/min)		
	2	4	8
PEEP			
0	34.75	—	69.5
5	35	—	69.5
10	35.25*	—	70.25*
15	35.5*	—	71*
I/E ratio			
1/1	36**	50**	75.5**
1/2	34.8	46.6	69.5
1/4	34.5	47.5**	70.5**
1/9	35.5**	48.5**	72.5**

I/E = inspiratory-to-expiratory ratio; OC = oxygen concentrator; PEEP = positive end-expiratory pressure.
*$p < .01$ compared with PEEP of 0 cmH$_2$O with I/E ratio of 1/2; respiratory rate (RR), 12/min; and tidal volume (VT), 500 mL.
**$p < .01$ compared with I/E ratio of 1/2 with PEEP of 0 cmH$_2$O; RR, 12/min; and VT, 500 mL.

Table 5 *Factors Influencing Delivered Fraction of Inspired Oxygen*

Factor	*p* Value
OC flow	<.0001
MV	<.0001
I/E	.022
PEEP	.046

I/E = inspiratory-to-expiratory ratio; OC = oxygen concentrator; PEEP = positive end-expiratory pressure; MV = minute ventilation.

The French Army is deployed in the African desert with light, mobile units providing intensive care and surgery close to the point of battlefield injury. Logistic support for the FSU is a difficult challenge. Compressed oxygen is routinely one of the first needs in intensive care or anesthesia. Oxygen resources in our current location are severely limited, and oxygen delivery for ventilated patients can be challenging in any austere environment. The use of cumbersome oxygen production modules is not possible in these settings. FSUs have a few high-pressure oxygen cylinders, and OC for production of low-pressure oxygen. The predictable difficulty in resupplying oxygen cylinders and use of OC are factors influencing the choice of ventilators in such contexts. Some ventilators functioning with a piston, turbine, or compressor do not need compressed gas to generate flow and may be used with a low-pressure oxygen source. The Elisée 350 ventilator is one such modern ventilator chosen by FMHS for its ventilation capabilities[8] to equip FSUs and for the possibility to be supplied by a low-pressure oxygen source. Boussen et al. tested several transport ventilators and showed the Elisée 350 was appropriate to deliver mechanical ventilation to critically ill patients, with a level of performance comparable to an intensive care unit ventilator.[8] Additionally, they showed this ventilator has a short, useful duration of 2 hours and 45 minutes when it is used with a 1,000L compressed oxygen cylinder (ventilator settings: F_{IO_2}, 1; PEEP, 5; tidal volume, 500mL; rate, 12). That is more than the LTV 1000 ventilator, which is known to be a high consumer of compressed oxygen (duration is less than 40 minutes with 700L of oxygen in a cylinder), due to a constant flow of 10L/min during exhalation to allow stabile PEEP.[9] The lower oxygen consumption of the Elisée 350 may be explained by a smaller turbine that requires less oxygen flow; however, it still would require too much flow in the primary inflow port to drive mechanic ventilation in a low-resources context.

Turbine technology, however, allows the Elisée 350 ventilator to operate without any external compressed gas source.[10] This is important because the oxygen supply in remote and low-resources contexts can be unobtainable or cumbersome. Coupled with the OC, the Elisée 350 ventilator has the capability to lessen the high consumption of oxygen. Indeed, when selected, the "low pressure O_2 source" option allows oxygen to be supplied from a low-pressure oxygen source. Oxygen from the low-pressure source is mixed with air inside the ventilator. The low-pressure oxygen source can be a line-mounted flow meter or an OC.

OCs require little maintenance to provide supplemental oxygen. The main limitation for use in critically ill ventilated patients is the oxygen flow provided. Initially, FMHS equipped the FSUs with a model of OC limited to 5L/min, which was insufficient to supply a ventilator.[11] Technological developments led to the production of OCs with higher oxygen flow. The SeQual Integra 10-OM concentrator typically delivers an F_{IO_2} up to 90%[7], and is capable of producing up to 10L/min of oxygen. This model is currently used by the FSUs.

Mechanical ventilators used with a high-pressure source of oxygen can deliver a precise F_{IO_2}. When oxygen is supplied by low pressure, the F_{IO_2} delivered to the patient cannot be precisely maintained. F_{IO_2} is determined by the oxygen inlet flow and the total minute volume adjusted on the ventilator. Results show that the respiratory rate and oxygen inlet flow are the main factors that affect delivered F_{IO_2} when a ventilator is used with a low-pressure oxygen source. Changes in I/E and PEEP result in statistically significant differences in delivered F_{IO_2}, although these differences are probably not clinically relevant because the difference is less than 3%. The maximum delivered F_{IO_2} will be limited by the liter-per-minute output of the OC and the total minute ventilation. As a result, ventilator parameters have to be chosen by a clinician and then the inlet oxygen flow should be adapted to reach the desired F_{IO_2}. Our results can help clinicians set the OC oxygen flow to obtain the desired F_{IO_2} based on the patient's minute ventilation (Figure 2).

We tested a compact OC used in French FSUs limited to an oxygen flow of 10L/min. However, stationary OCs are commonly used in the home by patients with chronic lung disease, and some of them are capable of much higher flows. Development of portable OCs with such capacities would allow clinicians to ventilate patients requiring both high F_{IO_2} and minute ventilation using a low-oxygen-consumption system. Currently, portable OC alone is inadequate to achieve an F_{IO_2} of greater than 80% at usual ventilation rates, or 60% for minute ventilation above 10L/min; thus, a high-pressure source is preferred.

Finally, the tested system is able to provide high F_{IO_2} levels without oxygen-cylinder consumption. However, it seems essential to monitor delivered F_{IO_2} when ventilators are used with low-pressure sources of oxygen because many factors affect F_{IO_2}.

Limitations of Our Study

F_{IO_2} measurement with an internal ventilator sensor is a limitation. Ventilators were new and specific technical calibrations were performed 3 months before the study. We assumed the oxygen sensor was still in calibration but cannot give an independent verification. We attempted to mitigate any error by using each ventilator with each individual OC. In addition, we also have not studied patient oxygenation to determine whether the delivered F_{IO_2} change affected arterial oxygenation. However, it was not our end point, and we did not pursue this for ethical concerns.

Conclusion

Our study demonstrates that a compact OC is a feasible alternative to oxygen cylinders to deliver high F_{IO_2} with the Elisée 350 turbine ventilator. The main difference when mechanical ventilation is performed with a low-pressure oxygen source is that changing ventilator settings or oxygen flow leads to variations in the amount of delivered F_{IO_2}. It is important to monitor and adjust flow to maintain desired F_{IO_2} during such circumstances.

Disclosures

The authors have nothing to disclose.

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