Oxygen Consumption with Mechanical Ventilation in a Field Anesthesia Machine

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Field anesthesia machines (FAM) with gas-powered ventilators have been developed for remote locations that may not have a central supply of oxygen. These ventilators may rapidly deplete oxygen cylinders, especially in patients with decreased pulmonary compliance. Our goal in this study was to determine oxygen consumption rates with a contemporary FAM in models of high (HC) and low (LC) pulmonary compliance. Oxygen consumption rates were tested using D cylinders (initial pressure 1700 psig) and the Narkomed® M FAM, which uses an air injector to decrease compressed gas consumption by entraining room air as part of the drive gas. Three different tidal volumes (VT) were tested (500, 750, and 1000 mL) with HC and LC lung models, and the fresh gas flow rate was 1 L/min. Respiratory rate was constant at 10 breaths/min. Oxygen consumption varied directly with VT and inversely with compliance, increasing from 4.8 ± 0.07 L/min with the HC-500 mL VT model to 6.2 ± 0.05 L/min with the LC-1000 mL VT model. D cylinder duration ranged from 56.8 ± 0.4 to 73.6 ± 1.0 minutes. Assuming oxygen fresh gas flow of 1 L/min, calculating tank duration with the fastest consumption rate underestimated the tank duration for more compliant and smaller VT models but provided a greater margin of patient safety.

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Anesthesiologists work in remote locations both inside and outside the fixed hospital setting, providing anesthetics for office-based, humanitarian, and military interventions. Space limitations often preclude the use of anesthesia systems present in the fixed hospital operating room (OR), especially when working in austere field conditions. These space limitations led to the development of alternate anesthesia machines. These so-called field anesthesia machines (FAM) have evolved significantly during the last decade (1). Contemporary FAMs are functionally equivalent to the anesthesia machines in the fixed hospital OR, which is a requirement of the ASA Guidelines for Nonoperating Room Anesthetizing Locations (2). This equivalence includes the ability to provide gas-powered mechanical ventilation.

Gas-powered ventilators consume drive gas at a high rate (3). As adverse outcomes in office-based settings have been linked to a lack of supplemental oxygen (4), the use of gas-powered ventilation in settings with limited gas supplies directly impacts on patient safety. Because "the backup oxygen system should include the equivalent of at least a full E cylinder" (2), knowing the drive gas consumption rate is essential to estimating cylinder duration. A previous study (3) investigating tank depletion rates with the Narkomed® 2B (North American Draeger®, Telford, PA) and the Ohmeda® 7000 (Datex-Ohmeda, Helsinki, Finland) ventilators found a slower depletion rate with the former because its air injector decreases compressed gas consumption by entraining room air as part of the drive gas. However, that study only tested a high compliance (HC) lung model with a tidal volume (VT) of 500 mL. The data generated in that previous study may not be directly applicable to patients requiring larger VT or with decreased pulmonary compliance. Because cylinder duration affects patient safety, we measured drive gas consumption rates with a contemporary FAM in models of both HC and low pulmonary compliance (LC).

Methods

After obtaining institutional approval, the oxygen consumption rates were determined with the Narkomed® M FAM (North American Draeger®) when mechanically

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Table 1. High Compliance Lung Model Ventilator Settings

Tidal volume (mL)	Inspiratory flow	Peak pressure (cm H_2O)	Mean pressure (cm H_2O)	Compliance (mL/cm H_2O)
500	ML (b)	16	5	36
750	HL (c)	19	6	39
1000	LM (d)	26	8	42

Compliance calculated as tidal volume/(peak pressure − positive end-expiratory pressure). Positive end-expiratory pressure = 2 cm H_2O in all groups. ML = mid-low; HL = high-low; LM = low-medium.

Table 2. Low Compliance Lung Model Ventilator Settings

Tidal volume (mL)	Inspiratory flow	Peak pressure (cm H_2O)	Mean pressure (cm H_2O)	Compliance (mL/cm H_2O)
500	LM (b)	24	9	23
750	LM	31	9	26
1000	MM (c)	53	14	20

Compliance calculated as tidal volume/(peak pressure − positive end-expiratory pressure). Positive end-expiratory pressure = 2 cm H_2O in all groups. LM = low-medium; MM = mid-medium.

ventilating and supplied by D cylinders. Detailed product information and photographs of the FAM model used in this study are available at the manufacturer's Web site (5). A certified technician performed machine preventive maintenance, and all tests were done with the same machine. The anesthesia machine's cylinder pressure gauge reading corresponded with the D cylinders' pressure of 1700 psig.

Three different V_T (500 mL, 750 mL, and 1000 mL) were tested with both LC and HC lung models, for six groups. Four tanks were tested in each group. A new disposable circle anesthesia circuit was used for each group (Sims Portex®, Fort Myers, FL). The lung model for each HC test was a new 3-L breathing bag (Sims Portex®). The Siemens® Test Lung 190 (Siemens AG®, Munich, Germany) was used for the LC model.

Circuit pressures and V_T were measured using the FAM's airway pressure transducer and spirometer, respectively. The dynamic compliance (C_{DYN}) of the lung model for each group was calculated as follows: C_{DYN} = V_T/(peak airway pressure − positive end-expiratory pressure [PEEP]) (Tables 1 and 2). PEEP was 2 cm H_2O in all groups.

The Food and Drug Administration recommended machine check was performed before the first test of the day, and an abbreviated check was performed between tests. An H cylinder provided the pipeline oxygen supply while the ventilator and machine settings were adjusted and verified. Respiratory rate was 10 breaths/min and the I:E ratio was 1:2. V_T was set by moving the ventilator bellows adjustment plate until the measured exhaled V_T equaled 500 mL, 750 mL, or 1000 mL. Fresh gas flow (FGF) was limited to 1 L/min. Because drive gas in the Narkomed® M vents to the atmosphere when ventilating with an inspiratory pause (6), the inspiratory flow was limited to the setting that fully compressed the bellows without an inspiratory pause. After verification of the settings, the pipeline supply hose was disconnected from the machine. When the low oxygen supply pressure alarm sounded, the D cylinder was opened, and the time until the low oxygen supply pressure alarm next sounded was recorded.

To perform calculations, a full D cylinder's pressure and volume were assumed to be 1900 psig and 400 L, respectively (7). The low oxygen supply pressure alarm threshold was assumed to be 35 psig. Because the D cylinders available for this study were not consistently filled to a pressure of 1900 psig, a pressure of 1700 psig was chosen. The initial volume was therefore calculated as 400 L × (1700 psig/1900 psig) = 358 L. The volume used from the cylinders was then calculated as 358 L − (400 L × 35 psig/1900 psig) or 351 L.

Statistical calculations were done using Excel2000® (Microsoft Corporation, Redmond, WA) and Primer of Biostatistics® (Version 4.02, McGraw-Hill, New York, NY). Drive gas consumption rates were compared to minute ventilation ($\dot{V}_E$) with linear regression analysis. Between-group comparisons with the same V_T were analyzed using independent sample Student's *t*-tests. Among-group comparisons with the same lung model were analyzed using repeated-measures analysis of variance with the Student-Newman-Keuls test for multiple comparisons. The data were reported as mean (± SD), and $P < 0.05$ was accepted as significant.

Results

The time until the low oxygen supply pressure alarm sounded for the HC lung model was more than the LC lung model at each tested volume ($P < 0.001$, Table 3). When D cylinders containing 358 L supplied oxygen for FGF and powered the ventilator, the time until the

Table 3. Narkomed® M Ventilator D cylinder Duration

Tidal volume (mL)	High compliance	Low compliance	*P* value
500	73.6 ± 1.0*	64.8 ± 1.2*	<0.001
750	68.0 ± 0.9*	61.5 ± 1.2*	<0.001
1000	63.4 ± 0.6*	56.8 ± 0.4*	<0.001

Values are mean ± SD (min).
* $P < 0.05$ compared with other same compliance groups.

low oxygen supply pressure alarm sounded ranged from 56.8 ± 0.4 to 73.6 ± 1.0 min (Table 3). For each VT tested, the cylinder gas consumption rate with the HC lung model was less than the cylinder gas consumption rate with LC lung model ($P < 0.001$) (Fig. 1) and increased from 4.8 ± 0.07 L/min with the HC-500 mL VT model to 6.2 ± 0.05 L/min with the LC-1000 mL VT model. The cylinder gas consumption rate correlated highly with $\dot{V}$E, with r^2 values of 0.980 and 0.993 for the HC and LC lung models, respectively (Fig. 1).

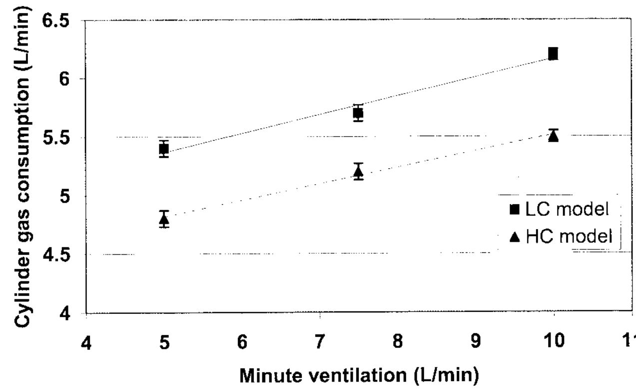

Figure 1. Cylinder gas consumption versus minute ventilation with fresh gas flow of 1 L/min. Results are means ± SD $P < 0.001$ for all same minute ventilation group comparisons, and $P < 0.05$ for all same lung model group comparisons. LC = low compliance, HC = high compliance.

Discussion

This study demonstrated that the oxygen consumption rates in a contemporary FAM using mechanical ventilation increased with both increasing $\dot{V}$E and decreasing pulmonary compliance. Using the fastest consumption rate, obtained in the LC-1000 mL VT model, a full D cylinder will supply oxygen for approximately 1 hour when mechanically ventilating with a FGF of 1 L/minute.

These results compare favorably to data reported elsewhere (3,6,8). Cicman et al. (6) reported the ventilator's oxygen consumption rate with a medium inspiratory flow control setting as 12.5 L/min but did not describe a lung model or other ventilator settings. Taenzer et al. (3), using a HC-500 mL VT lung model, demonstrated that with a FGF of 1 L/minute and a respiratory rate of 10 breaths/minute, the E cylinder duration was 99 minutes. Assuming a 650-L oxygen supply with the E cylinder, the total oxygen consumption (from both FGF and the Narkomed® 2B ventilator) was 6.6 L/min. This cylinder depletion rate was approximately 38% more than that obtained with the Narkomed® M FAM using the same lung model. Klemenzson and Perouansky (8) used a different HC lung model (ventilator tester, BIO-TEK®, Winooski, VT) with the Narkomed® AV-2 ventilator and demonstrated a total oxygen consumption (FGF = 1 L/minute, VT = 700 mL, $\dot{V}$E = 7 L/minute) of 7.0 L/minute. This cylinder depletion rate was approximately 35% more than that obtained with the Narkomed® M FAM with a larger VT of 750 mL.

The reason for these differences may be the lower inspiratory flow control setting with the FAM (mid-low versus low-medium), which was selected to eliminate the inspiratory pause. When the Narkomed® ventilator delivers an inspiratory pause, drive gas continues to flow to the valve case assembly en route to the bellows canister. When the bellows canister has reached its volume limit, any additional drive gas is vented to the atmosphere via the valve case assembly (6). Therefore, eliminating the inspiratory pause should conserve drive gas.

Strategies for minimizing the use of compressed oxygen by the ventilator include maintaining spontaneous ventilation or using manual ventilation, although these may not be practical in an austere environment depending on the surgical procedure or necessity for the clinician to multitask. Because drive gas consumption is proportional to the $\dot{V}$E, setting a smaller $\dot{V}$E can reduce it, but this may not be practical if hyperventilation is indicated. Minimizing FGF via closed-circuit anesthesia will also conserve cylinder oxygen for use as drive gas. Another strategy is to use a different gas to power the ventilator. The Narkomed® M FAM can use air, instead of oxygen, as the drive gas. Selecting air as drive gas requires simply changing the drive gas selection toggle switch from oxygen to air, but implementation of this strategy depends on the availability of a compressed air supply. Finally, although not an option with the FAM used in this study, an electrically driven ventilator would maximize medical gas availability for the patient (9,10).

Although the LC lung model was not as sophisticated as other commercially available models, the C_{DYN} values obtained with it were comparable to those reported for patients with adult respiratory distress syndrome (ARDS) (11) and status asthmaticus (12) (25 and 20 mL/cm H_2O, respectively). The C_{DYN} of the LC lung model was also comparable to that reported in a group of 118 intensive care unit patients with respiratory failure (13). The etiologies of respiratory failure in 65% of those patients were pneumonia, chronic obstructive pulmonary disease,

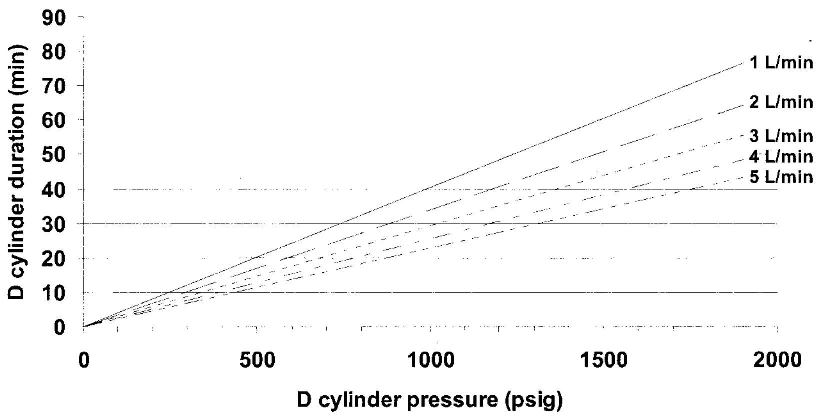

Figure 2. Estimated D cylinder duration in a high compliance (HC) 750 mL tidal volume with fresh gas flow of 1 to 5 L/min. Estimates extrapolated from data generated with the Narkomedâ M field anesthesia machine with a HC 750 mL tidal volume model and fresh gas flow of 1 L/min.

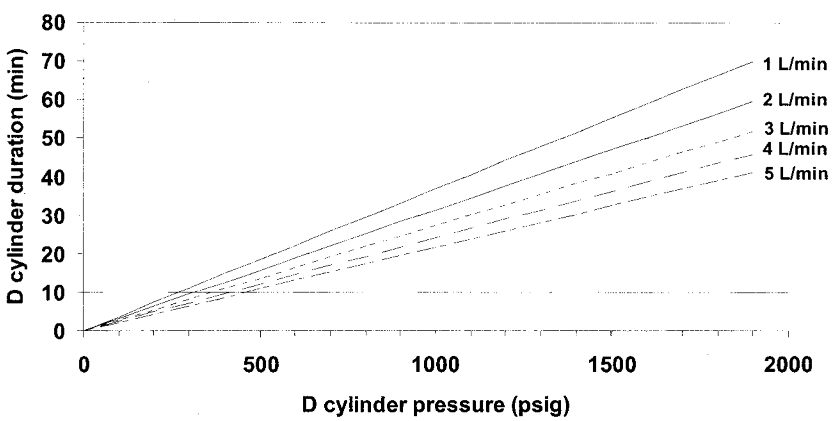

Figure 3. Estimated D cylinder duration in a low compliance (LC) 750 mL tidal volume with fresh gas flow of 1 to 5 L/min. Estimates extrapolated from data generated with the Narkomedâ M field anesthesia machine with a LC 750 mL tidal volume model and fresh gas flow of 1 L/min.

and ARDS, whereas the C_{DYN} was in the 22 to 24 mL/cm H_2O range.

A limitation of this study was that it did not model clinical events (e.g., induction and emergence) or disease states requiring a higher FGF. In addition to the increased oxygen needed to power a ventilator, a patient with poorly compliant lungs may have injury or illness that will increase metabolic oxygen requirements. To compensate for these limitations, graphs of D cylinder duration with various cylinder pressures and FGF were extrapolated from the HC and LC 750 mL VT models and included as a guide for clinicians using this FAM (Figs. 2 and 3).

In conclusion, oxygen consumption rates in a contemporary FAM with gas-powered mechanical ventilation were directly proportional to VT and inversely proportional to pulmonary compliance. With a FGF of 1 L/minute, calculating tank duration with the fastest consumption rate (6.2 L/minute, obtained from the LC-1000 mL VT model) underestimates the tank duration for more compliant and smaller VT models, while providing a greater margin of patient safety.

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