# Contemporary anesthesia ventilators incur a significant "oxygen cost"

## *[Les ventilateurs d'anesthésie actuels exposent à une importante «dépense d'oxygène»]*

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**Purpose:** Anesthesia ventilators use oxygen or oxygen/air mixtures to drive the bellows during controlled ventilation. As a practitioner may find himself in a situation that the only available oxygen source is a compressed oxygen cylinder, it is important to know the oxygen consumption of anesthesia ventilators during controlled ventilation.

**Methods:** We tested the Datex-Ohmeda 7900 ventilator mounted on an Excel 210 anesthesia machine under a variety of conditions. For comparison, we also tested the Ohmeda 7800 and the Dräger AV-2 ventilator under control conditions. All experiments were performed using a test lung.

**Results:** The oxygen consumption of the AV-2 and the Datex-Ohmeda ventilators averaged 302 ± 17 $L \cdot hr^{-1}$ and 564 ± 68 to 599 ± 56 $L \cdot hr^{-1}$, respectively ($P < 0.01$ AV-2 *vs* 7800 and 7900). When using an E-type cylinder, this would result in a mean time to alarm of 93 min and 54 to 57 min, respectively. Decreased lung compliance increased the oxygen consumption to 848 ± 16 $L \cdot hr^{-1}$.

**Conclusions:** Machine-driven mechanical ventilation incurs a significant "oxygen cost." We show that the amount of oxygen consumed by mechanical ventilation with contemporary anesthesia ventilators is influenced by patient-dependent factors and may greatly exceed the amount of oxygen delivered to the patient.

***Objectif :*** *Les ventilateurs d'anesthésie utilisent de l'oxygène ou des mélanges d'oxygène et d'air pour activer les soufflets pendant la ventilation contrôlée. Comme un médecin peut se retrouver dans la situation où la seule source d'oxygène disponible est une bouteille d'oxygène comprimé, il est important de connaître la consommation d'oxygène des ventilateurs d'anesthésie pendant la ventilation contrôlée.*

***Méthode :*** *Nous avons testé le ventilateur Datex-Ohmeda 7900 monté sur un appareil d'anesthésie Excel 210 dans diverses situations. À titre de comparaison, nous avons aussi testé les ventilateurs Ohmeda 7800 et Dräger AV-2 selon des conditions témoins. Toutes les expérimentations ont été réalisées avec un poumon d'essai.*

***Résultats :*** *La consommation d'oxygène des ventilateurs AV-2 et Datex-Ohmeda affichait une moyenne de 302 ± 17 $L \cdot h^{-1}$ et 564 ± 68 à 599 ± 56 $L \cdot h^{-1}$, respectivement ($P < 0,01$ AV-2 vs 7800 et 7900). Quand on a utilisé une bouteille de type E, le temps moyen précédant l'alarme était de 93 min et de 54 à 57 min, respectivement. Une diminution de la compliance pulmonaire augmentait la consommation d'oxygène à 848 ± 16 $L \cdot h^{-1}$.*

***Conclusion :*** *La ventilation mécanique produite par soufflets expose à une importante «dépense d'énergie». Nous montrons que la quantité d'oxygène consommé par la ventilation mécanique avec les ventilateurs d'anesthésie modernes est influencée par des facteurs reliés au patient et peut grandement dépasser la quantité d'oxygène administrée au patient.*

VENTILATORS on contemporary anesthesia machines commonly used in North America rely either partially or completely on oxygen ($O_2$) to drive their bellows. This implies that, if pipeline $O_2$ supply fails, $O_2$ from the $O_2$ cylinder will be used not only to supply the patient's needs but will also be diverted to compress the bellows of the ventilator. The impact of this "dual" use on the length of time that a given amount of $O_2$ will last is difficult to estimate: no specifications are provided by the manufacturers' manuals and the rule of thumb employed by practitioners (gas requirement for mechanical ventilation = gas volume delivered to the

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The results have been presented in part at the American Society of Anesthesiologists annual meeting in Orlando, Florida, USA Oct 2002.
*Accepted for publication December 8, 2003.*
*Revision accepted March 26, 2004.*

patient) has not been tested experimentally. Using a test lung, we measured the $O_2$ consumption of three commonly used ventilators under standard operating room conditions. In addition, in order to examine whether ventilator- and patient-dependent variables affect these requirements, we tested a single ventilator (Datex-Ohmeda 7900) using also pressure-controlled ventilation, positive end-expiratory pressure (PEEP) and varying compliances of the test lung. The data obtained from these experiments provide the clinician with information on the $O_2$ requirements for ventilating patients under varying clinical conditions.

## Materials and methods

We tested the Datex-Ohmeda ventilator types 7800 and 7900 mounted on the Excel and the Modulus SE anesthesia machines, respectively (Datex - Ohmeda, Madison, WI, USA) and the North American Dräger AV-2 on the Narkomed 2C machine (Dräger AV-E, Telford, PA, USA). For simplicity we will refer to the ventilators as 7800, 7900 and AV-2 in the text. We conducted the experiments in operating rooms with the thermostat set at 21°C (actual temperature ranged from 21 to 25°C). On each experimental day, the barometric pressure was obtained from the local weather station. The pressure ranged from 746 to 767 mmHg (mean 754 ± 5), a variation of less than 3% that we considered not significant for our calculations. We used full E-type $O_2$ cylinders (5-L, containing 660 L of $O_2$ at 13,000 kPa) and adult breathing circuits with 3 L rebreathing bags. After checking for leaks, the circuit was connected to the test lung (ventilator tester, BIO-TEK, BIO-TEK Instruments, Inc., Highland Park, Winooski, VT, USA). None of the experiments were performed on living subjects. The fresh gas flow (FGF) was set at 2 $L\cdot min^{-1}$ in a semi-open circuit configuration. Delivered volumes were tested with the test lung.

The amount of $O_2$ consumed to drive the bellows was determined as follows: the anesthesia machine was disconnected from the wall gas supply with all flow metres set to zero flow. A full E-type cylinder was installed. The FGF was set at 5 L $O_2\cdot min^{-1}$ (to fill the circuit). Mechanical ventilation was initiated and, after two minutes, the FGF was reduced to 2 L $O_2\cdot min^{-1}$ for the rest of the experiment.

Tidal volumes ($V_T$), peak, mean and minimal circuit pressures were continuously monitored with the built-in spirometer and confirmed with the test lung at least twice during the experiment. If set and measured $V_T$s differed by more than 10% the experiment was discontinued.

Exactly 30 min after the start of the experiment the anesthesia machine was turned off, the $O_2$ cylinder closed and released from the anesthesia machine. The total volume of $O_2$ (VTOT) consumed during the experiment was determined from the difference in the mass of the cylinder before and after the experiment using the ideal gas-equation $VTOT = [\Delta m \times [(273 + (T_{amb})/273] \times 22.4\ L \times mol^{-1})]/32\ g \times mol^{-1}$,[1] where $\Delta m$ = weight of cylinder in grams at the beginning minus weight after the experiment, $(T_{amb})$ = numerical value of measured ambient temperature in degrees celcius, 22.4 L and 32 g are the volume at 0°C and the weight of one mole of $O_2$. The scales used to measure the cylinder's weight were precise to ± 1 g (± 0.75 L $O_2$ at 20°C). The $O_2$ requirements of the ventilator (Vvent) over the 30 min of experiment were calculated by subtracting the FGF from VTOT: $Vvent = VTOT - (5\ L\cdot min^{-1} \times 2\ min + 2\ L\cdot min^{-1} \times 28\ min)$ and converted to litres per hour. Oxygen requirements were compared using the non-paired t test, a *P*-value of < 0.05 was considered significant.

For experiments under standard conditions, the ventilator was set to deliver a $V_T$ of 700 mL at a rate of 10 $breaths\cdot min^{-1}$. The delivered volume was tested with the test lung and the ventilator settings adjusted to deliver a measured $V_T$ of 700 ± 70 mL. This was done with the anesthesia machine connected to central gas supply. Test lung compliance and airway resistance were set at 50 mL/cm $H_2O$ and 20 cm $H_2O/L\cdot min^{-1}$ (normal values from BIO-TEK Instruments Inc., Winooski, VT, USA), respectively. For some experiments with the 7900 these variables were adjusted on the test lung as follows: in order to simulate lungs with high and low compliances (e.g., open chest *vs* adult respiratory distress syndrome) the compliance of the artificial lung was set at 100 and 20 mL/cm $H_2O$, respectively. For experiments involving pressure-controlled ventilation the inspiratory pressure was adjusted to deliver a $V_T$ of 700 mL as measured by the test lung. We performed a total of 41 experiments. The number of experiments performed with each ventilator ranged from three to five for each condition tested.

## Results

The $O_2$ requirement of the tested anesthesia ventilators varied widely between the ventilators and the various experimental conditions, ranging from 302 ± 17 $L\cdot hr^{-1}$ (AV-2 under control conditions) to 848 ± 16 $L\cdot hr^{-1}$ (7900 and noncompliant lungs, $P < 0.01$).

### *Control conditions*

The measured $O_2$ requirements of the tested ventilators under control conditions are presented in Table I. The Ohmeda ventilators required significantly more $O_2$ to drive the ventilator bellows than the Narkomed.

TABLE I $O_2$ consumption of anesthesia ventilators under control conditions

| *Ventilator (mode)* | *n* | *Δ mass in g (mean ± SD)* | *Δ volume in L (mean ± SD)* | *$O_2$ consumption L·hr$^{-1}$ (mean ± SD)* |
|---|---|---|---|---|
| 7800 (VC) | 3 | 453 ± 22 | 344 ± 27 | 564 ± 68 |
| 7900 (VC) | 5 | 480 ± 15 | 365 ± 28 | 599 ± 56 |
| 7900 (PC) | 3 | 486 ± 8 | 365 ± 15 | 598 ± 30 |
| AV-2 (VC) | 3 | 288 ± 7 | 217 ± 9 | 302 ± 17 |

Determination of oxygen ($O_2$) consumption under control conditions [tidal volume: 700 mL; compliance 50 mL/cm $H_2O$; positive end-expiratory pressure (PEEP) 0; 10 breaths·min$^{-1}$]. The mass lost from the $O_2$ tanks (Δ mass) was converted into litres $O_2$ using the ideal gas equation. VC and PC indicate volume-controlled and pressure-controlled ventilation, respectively; *n* refers to the number of experiments; SD is standard deviation.

TABLE II Calculated time to low-pressure alarm signal

| *Ventilator (mode)* | *Lung compliance* | *$VO_2$ in L·min$^{-1}$* | *Time to alarm E-type* | *Time to alarm H-type* |
|---|---|---|---|---|
| AV-2 (VC) | normal | 5 | 93 min | 16 hr 12 min |
| 7800 (VC) | normal | 9.4 | 57 min | 9 hr 57 min |
| 7900 (PC) | normal | 10 | 54 min | 9 hr 27 min |
| 7900 (VC) | high | 9.1 | 59 min | 10 hr 13 min |
| 7900 (VC) | normal | 9.4 | 54 min | 9 hr 27 min |
| 7900 (VC) | low | 11.8 | 47 min | 8 hr 13 min |
| 7900 (VC) PEEP 10 | low | 14.8 | 39 min | 6 hr 45 min |

Time available until the low-pressure alarm signal indicating that the pressure in the cylinder has dropped to 207 kPa will be activated, assuming a full E-type cylinder (660 L, 13,000 kPa) or H-type cylinder (6900 L, 15,000 kPa) is used.[4]

Under control conditions, the 7900 and 7800 ventilators required approximately twice as much $O_2$ as the AV-2 (599 ± 56 and 564 ± 68 *vs* 302 ± 17 L·hr$^{-1}$, $P < 0.01$). Selecting pressure-controlled ventilation instead of volume-controlled ventilation to deliver the same minute volume did not change the driving gas requirements of the 7900 ventilator (598 ± 30 L·hr$^{-1}$).

*Varying compliance*

After obtaining measurements under control conditions we tested the 7900 on an artificial lung with high and low compliance (100 and 20 mL/cm $H_2O$). As PEEP is routinely used when ventilating patients with non-compliant lungs, we also tested the 7900 adding 10 cm $H_2O$ of PEEP. The results of these experiments are shown in the Figure. The driving gas requirements increased with decreasing compliance from 543 ± 7 L·hr$^{-1}$ at the highest compliance tested to 848 ± 16 L at the lowest compliance + PEEP. This difference was statistically significant ($P < 0.05$).

*Time to low pressure alarms*

Using the measured $O_2$ requirements, we calculated the time it would take for the low-$O_2$ alarm to be activated (the experiments lasted for 30 min, which was not enough to deplete the $O_2$ tanks sufficiently). When using an E-type cylinder (5-L, typically used as an emergency back-up) and assuming that the $O_2$ requirements remain constant as the cylinder empties, the time to activation of the low-$O_2$ alarm would range from 93 min (AV-2) to 57 min (7800). When ventilating a test lung with low compliance, the time would be reduced to 39 min. The results of the calculations are summarized in Table II. We included also calculations for H-type cylinders (46 L: ± 6900 L of $O_2$ at 15,000 kPa)[4] as these are frequently used in locations without access to central $O_2$ supply.

## Discussion

Anesthesia machine-mounted ventilators use $O_2$ or $O_2$/air mixtures to drive the bellows during mechanical ventilation. We have measured the $O_2$ requirements of three anesthesia machine-mounted ventilators representing two different technological principles of driving gas delivery (Ohmeda *vs* North American Dräger) and two different "generations" of anesthesia ventilators (7800 *vs* 7900) under standard operating room conditions. Quantifying the $O_2$ requirements of anesthesia ventilators is important: anesthetic care may have to be provided without

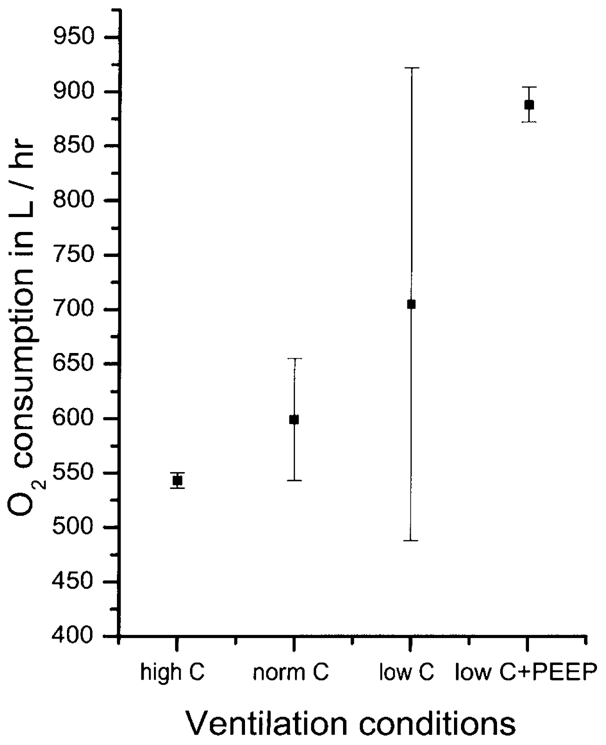


FIGURE Lung compliance affects oxygen ($O_2$) requirements. The $O_2$ consumption of the Datex Ohmeda 7900 ventilator increased progressively with decreasing lung compliance (C). The error bars are the standard deviations. The difference between the high compliance state (high C) and the low compliance state + positive end-expiratory pressure (PEEP; low C + PEEP) was significant. Note the progressive increase in standard deviation with decreasing compliance in the absence of PEEP (see text for discussion).

access to central $O_2$ supply, in which case $O_2$ for driving the bellows will be drawn from the same source as for the patients' needs. This can occur either under elective (remote location) or emergent (pipeline failure) conditions. In either case, every anesthesiologist should be able to estimate the amount of $O_2$ required to maintain patient ventilation and oxygenation under given circumstances and to optimize controllable variables in order to maximize the amount of time the given $O_2$ supplies will last without endangering patient safety. This study provides the necessary data for three commonly used ventilators. These data are not available in the manufacturers' manuals and, though obtained in a different way, are consistent with and expand on a recently published report.[2]

Under control conditions ($V_T$ 700 mL, 10 breaths·min$^{-1}$, compliance 50 mL/cm $H_2O$, PEEP 0), the Ohmeda ventilators 7800 and 7900 had similar $O_2$ requirements ranging from 564 to 599 L·hr$^{-1}$ for the 7800 and the 7900, respectively ($P$ = 0.45). The Dräger AV-2 (with the inspiratory flow rate set to medium) required approximately 50% less $O_2$ than the Ohmeda ventilators (i.e., 302 ± 17 L·hr$^{-1}$). A difference in $O_2$ consumption was expected: during mechanical ventilation the AV-2 (like other North American Dräger ventilators) entrains air, exploiting the Venturi effect, and therefore drives the bellows with a gas mixture containing ± 33% entrained air when inspiratory flows are set to mid-range (North American Dräger, personal communication),[3] while Ohmeda ventilators compress the bellows with 100% $O_2$. Our experiments show that using a rule of thumb (e.g., driving gas = minute ventilation) generally underestimates the actual driving gas requirements of the ventilators. Under baseline conditions we ventilated with a minute ventilation of 7 L, i.e., 420 L·hr$^{-1}$ (excluding FGF). This would result in an estimated driving gas requirement of ± 420 L and ± 280 L of $O_2$ per hour for the Ohmeda and the Dräger ventilators (assuming 33% entrained air in the driving gas for the latter): an underestimate of the actual consumption by 40% and 8%, respectively. Our data indicate that the error would be more significant when ventilating diseased lungs with low compliance.

Modern anesthesia ventilators offer the practitioner a choice between volume- and pressure-controlled ventilation. We examined whether driving gas requirements of the 7900 were affected by the choice of a specific ventilation mode. Under control conditions, there was no significant difference in driving gas requirements between volume-controlled and pressure-controlled ventilation (599 ± 56 *vs* 598 ± 30 L·hr$^{-1}$).

Finally, we defined the impact of varying lung compliance on driving gas requirements of the 7900. Decreasing lung compliance increased the driving gas requirements (Figure), but the difference reached statistical significance only for the most extreme case tested - a compliance of 20 mL/cm $H_2O$, still within the range encountered clinically. Therefore, the patient's lung compliance should be taken into account, even though its impact on $O_2$ consumption would probably remain unnoticed under usual clinical conditions. We noticed that the variability of the $O_2$ requirements of the 7900 increased with decreasing compliance of the test lung. As the experiments were performed on the same machine, variability between ventilators cannot account for this observation. While we do not have a simple explanation, we think it is possible that the microprocessor-controlled feedback circuitry of the 7900, that provides constant adjustments of delivered $V_T$s, might oscillate with increasing impedance of the breathing circuit. It is remarkable that application of PEEP reduced the variability dramatically (Figure).

Our results for ventilation under normal conditions are consistent with those obtained by Taenzer *et al.*[2] In addition, our data can also be used to estimate the length of time that ventilation can be maintained with any size cylinder, as long as the amount of stored $O_2$ is known.

In conclusion, we have measured the driving gas requirements of three contemporary anesthesia machine-mounted ventilators. In order to deliver 1 L of minute ventilation to the patient under control conditions, the Datex-Ohmeda 7800/7900 and Dräger's AV-2 ventilators required approximately 1.4 L and 0.69 L of $O_2$ driving gas, respectively. Ventilation of lungs with a low compliance increased the $O_2$ requirements significantly: in order to deliver 420 L of minute ventilation, the 7900 required ± 848 L of $O_2$, that is more than 2 L of driving gas per litre of minute ventilation. This translates into a reduction of the time an E-type cylinder would support ventilation from 54 to 39 min.

## Acknowledgements
We would like to thank Robert Q. Tham and Mr. John Pinkert from Datex-Ohmeda, Madison, WI, USA for advice and for providing us with the Bio-Tek ventilator tester and Dr. G. Arndt for critically reading the manuscript.

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