Oxygen Consumption of a Pneumatically Controlled Ventilator in a Field Anesthesia Machine

Dale F. Szpisjak, MD, MPH*

Elizabeth N. Javernick, MD†

Richard R. Kyle, MS‡

Paul N. Austin, PhD, CRNA§

BACKGROUND: Field anesthesia machines (FAM) have been developed for remote locations where reliable supplies of compressed medical gases or electricity may be absent. In place of electricity, pneumatically controlled ventilators use compressed gas to power timing circuitry and actuate valves. We sought to determine the total O_2 consumption and ventilator gas consumption (drive gas [DG] plus pneumatic control [PC] gas) of a FAM's pneumatically controlled ventilator in mechanical models of high (HC) and low (LC) total thoracic compliance.

METHODS: The amount of total O_2 consumed by the Magellan-2200 (Oceanic Medical Products, Atchison, KS) FAM with pneumatically controlled ventilator was calculated using the ideal gas law and the measured mass of O_2 consumed from E cylinders. DG to the bellows canister assembly was measured with the Wright Respirometer Mk 8 (Ferraris Respiratory Europe, Hertford, UK). PC gas consumption was calculated by subtracting DG and fresh gas flow (FGF) from the total O_2 consumed from the E cylinder. The delivered tidal volume (V_T) was measured with a pneumotach (Hans Rudolph, KS City, MO). Three different V_T were tested (500, 750, and 1000 mL) with two lung models (HC and LC) using the Vent Aid Training Test Lung (MI Instruments, Grand Rapids, MI). Respiratory variables included an I:E of 1:2, FGF of 1 L/min, and respiratory rate of 10 breaths/min.

RESULTS: Total O_2 consumption was directly proportional to V_T and inversely proportional to compliance. The smallest total O_2 consumption rate (including FGF) was 9.3 ± 0.4 L/min in the HC-500 model and the largest was 15.9 ± 0.5 L/min in the LC-1000 model ($P < 0.001$). The mean PC circuitry consumption was 3.9 ± 0.24 L/min or 390 mL ± 24 mL/breath.

CONCLUSIONS: To prepare for loss of central DG supply, patient safety will be improved by estimating cylinder duration for low total thoracic compliance. Using data from the smaller compliance and greatest V_T model (LC-1000), a full O_2 E cylinder would be depleted in <42 min, whereas a full H cylinder would last approximately 433 min.

(Anesth Analg 2008;107:1907–11)

Ventilators can be described as pneumatically or electrically controlled. This designation refers to the operation of the ventilator control circuit. The control circuit directs the function of the drive mechanism and/or output control valve. A pneumatically controlled ventilator has a pneumatic control (PC) circuit that uses small gas flows to generate signals that activate timing systems and pressure switches. They do not require electricity for operation of the control circuit but, rather, consume compressed gases.[1]

Field anesthesia machines (FAM) have been developed to support patient care in remote locations where reliable supplies of electricity and/or compressed medical gases may be absent. The use of pneumatically controlled ventilators is appealing in these locations because they are rugged, lightweight, have few moving parts, and do not require electrical power.[2] Although these characteristics facilitate their transportation and use in remote locations, their PC circuitry requires additional compressed gas beyond the drive gas (DG) needed to compress the ventilator bellows during positive pressure ventilation. Knowledge of the total compressed gas consumed by a FAM is important both for logistical and contingency planning. Although previous investigations[3–5] have determined the DG requirements of the Narkomed M FAM, the Narkomed 2B (North American Draeger, Telford,

Figure 1. Magellan-2200 FAM with model 1 ventilator. Front view of the Magellan-2200 FAM with model 1 ventilator used in this investigation.

PA), and the Datex-Ohmeda 7000 and 7900 ventilators (Datex-Ohmeda, Helsinki, Finland), these ventilators are not pneumatically controlled and, therefore, have no PC gas requirement.[6] Given that the compressed gas requirement of a ventilator impacts both logistics and patient safety, the purpose of this investigation was to determine the total O_2, the DG, and the PC gas consumed by a contemporary FAM with a pneumatically controlled ventilator in models of both high (HC) and low (LC) total thoracic compliance.

METHODS

Total compressed O_2 consumed by the Magellan-2200 FAM (Fig. 1) (Oceanic Medical Products, Atchison, KS) was measured for three different tidal volumes (V_T) delivered to lung models of both HC and LC total thoracic compliance. DG volume was measured with the Wright Respirometer Mark 8 (Ferraris Respiratory Europe, Hertford, England) installed on the DG inlet port of the bellows canister. Inspired V_T was measured with the RSS 100HR Research Pneumotach using the model 3700 Linear Pneumotach (Hans Rudolph, KS City, MO).

The pneumotach was calibrated for each compliance setting by delivering 1000 mL of air with the Series 5530 3-L calibration syringe (Hans Rudolph, KS City, MO, USA) while it was attached to the Vent Aid TTL Training Test Lung (TTL), (MI Instruments, Grand Rapids, MI) by a 23 cm length of 9.0 mm inner diameter plastic tubing. Upon completion of calibration, the pneumotach was set to measure 100% O_2, matching the gas delivered by the ventilator.

Because volume measured by the Wright respirometer depends on gas flow rate, calibration factors were determined by delivering 500, 750, and 1000 mL volumes of air through it with the calibration syringe after the Wright respirometer was attached to the DG inlet port of the bellows canister assembly. The circuit of the ventilator was attached to the TTL. The plunger of the syringe was stroked 10 times for each compliance V_T combination, thus acting as DG. The total

volume of gas delivered was then divided by 10 to determine the per breath calibration factor for each compliance V_T combination.

The two tested compliance settings of the TTL were confirmed by injecting 1000 mL of air with the calibration syringe into one of the mechanical lungs of the TTL while measuring the pressure increase with the auxiliary pressure port of the RSS 100HR Research Pneumotach after confirming its calibration against a column of water. The LC setting was 0.020 L/cm H_2O and the HC setting was 0.100 L/cm H_2O. No resistor was interposed between the ventilator and TTL, thus the resistance in the system was generated by the breathing tubing and connectors.

The Magellan-2200 FAM was assembled and the preuse check list completed per the manufacturer's instructions. Detailed information about this FAM and its ventilator are available at the manufacturer's web site (http://www.oceanicmedical.com/magellan_2200. php, accessed March 13, 2008). The model 3700 Linear Pneumotach was installed in-line between the Y-piece of an adult, semiclosed, circle anesthesia breathing system (King Systems Corporation, Noblesville) and the inlet port on the calibrated half of the TTL. To prevent the weight of the model 3700 Linear Pneumotach from changing the compliance of the lung model it was attached to the TTL with a 23 cm length of 9.0 mm inner diameter plastic tubing.

The ventilator respiratory rate (RR) was set to approximately 10 breaths/min by adjusting the inspiratory time to approximately 2 s and the expiratory time to approximately 4 s. The target V_T (500, 750, and 1000 mL ± 5%) was obtained by adjusting the ventilator inspiratory flow setting. The FAM was supplied with compressed O_2 via E cylinders regulated to 50–55 psig by the Model 1203 O_2 regulator (Air Products and Chemicals Inc., Allentown, PA). Fresh gas flow (FGF) rate was set to 1 L/min. Each data collection period lasted 20 min. Before and after each data collection period, the E cylinder was weighed to ± 1 g to determine the total mass of O_2 consumed from the E cylinder. The total volume of O_2 consumed was then calculated using the ideal gas equation, similar to the technique described by Klemenzson and Perouansky[5]:

$$\text{Consumed E cylinder } O_2 = ([\Delta m / 32 \text{ g} \cdot \text{mol}^{-1}]$$

$$\times 0.08205784 \text{L} \cdot \text{ATM} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \times [T_{amb}]) / P_{amb},$$

where Δm = change in mass of E cylinder after a data collection period,

T_{amb} = room temperature in °K, and

P_{amb} = barometric pressure obtained daily from the on-line weather report for Washington, DC available at http://www.washingtonpost.com.

For each 20-min data collection period, inspired V_T, inspiratory time, expiratory time, and peak inspiratory pressure (PIP) for each breath were recorded on a laptop computer using Research Pneumotach System

Table 1. O_2 Consumption of a Pneumatically Controlled Ventilator with FGF of 1 L/min

V_T (mL)	Compliance	PIP (cm H_2O)	Δ Mass (g)	ΔO_2 volume (L)	Total O_2 consumed (L/min)	Total ventilator O_2 consumed (L/min)	Drive gas (L/min)	Pneumatic control gas (L/min)
500	HC	7 ± 0.1	245 ± 1	185 ± 0.8	9.3 ± 0.04*†	8.3 ± 0.04*	4.5 ± 0.07*	3.8 ± .010
500	LC	29 ± 8	274 ± 6	208 ± 4	10.4 ± 0.21*	9.4 ± 0.21*	5.8 ± 0.08*	3.6 ± 0.14
750	HC	9 ± 0.4	316 ± 6	233 ± 4	11.6 ± 0.22*†	10.6 ± 0.22*	6.8 ± 0.18*	3.8 ± 0.24
750	LC	41 ± 0.1	345 ± 3	259 ± 2	12.9 ± 0.11*	11.9 ± 0.11*	8.3 ± 0.18*	3.7 ± 0.18
1000	HC	12 ± 0.1	383 ± 3	282 ± 2	14.1 ± 0.10*‡	13.1 ± 0.10*	9.3 ± 0.08*	3.8 ± 0.16§
1000	LC	54 ± 0.4	425 ± 12	318 ± 9	15.9 ± 0.45*	14.9 ± 0.45*	11.6 ± 0.44*	3.3 ± 0.14

n = 3 for each compliance V_T combination. Values are mean ± SD.

FGF = fresh gas flow; V_T = target tidal volume; HC = high compliance (0.10 L/cm H_2O); LC = low compliance (0.02 L/cm H_2O); PIP = peak inspiratory pressure.

* $P < 0.002$ compared to all other groups.

† $P = 0.0008$ for like V_T comparison.

‡ $P = 0.0025$ for like V_T comparison.

§ $P = 0.0191$ for like V_T comparison.

Windows Software version 3.07.04 (KORR Medical Technologies Inc., Salt Lake City, UT).

The rate (L/min) of total O_2 consumption by the ventilator (both DG and PC gas) was determined by calculating the volume of O_2 consumed from the tank, subtracting 20 L to account for the FGF during the data collection period, and then dividing by the duration of the data collection period in minutes. To determine the rate of DG consumption, the volume of gas flowing through the Wright respirometer was measured twice at approximately 5 minute intervals for 10 consecutive breaths. These volumes were averaged and the correction factor described above was applied to determine the DG volume per breath. This quantity was then multiplied by the number of breaths delivered during the data collection period and then divided by the duration of the data collection period to determine the DG consumption rate in L/min. The rate of PC gas consumption was calculated by subtracting the DG consumption rate from the total ventilator consumption rate.

The data were entered into an Excel 2003 spreadsheet (Microsoft Corporation, Redmond, WA). Statistical calculations were performed with Excel 2003 and Intercooled Stata 9.0 for Windows (StataCorp LP, College Station, TX). Between-group comparisons with the same V_T or lung compliance were analyzed using independent sample Student's t-test for equal or unequal variance, as appropriate. Among-group comparisons were analyzed using analysis of variance with the Bonferroni multiple comparison test. The data were reported as mean (±SD), and $P < 0.05$ was accepted as significant.

RESULTS

The total O_2 consumption of the pneumatically controlled ventilator supplied with the Magellan-2200 FAM ranged from 9.3 (±0.04) L/min in the HC-500 lung model to 15.9 (±0.45) L/min in the LC-1000 lung model ($P < 0.002$, Table 1). The ventilator gas requirement (DG plus PC gas) was directly proportional to V_T and indirectly proportional to compliance of the lung model. The lowest ventilator gas requirement was in the HC-500 lung model (8.3 [±0.04] L/min) whereas the greatest ventilator gas requirement was in the LC-1000 lung model (14.9 [±0.45] L/min, $P < 0.002$, Table 1). The ventilator gas required in the LC model exceeded the HC model for all like V_T groups ($P < 0.003$).

When all groups were pooled by compliance, the PC gas consumption rate was less in the LC lung model than in the HC lung model (3.52 [±0.21] vs 3.80 [±0.15] L/min, respectively; $P = 0.0053$). When comparing PC consumption rates for like V_T groups, the only difference was found in the $V_T = 1000$ mL groups ($P = 0.0191$).

DISCUSSION

This laboratory investigation demonstrated that the total O_2 consumption of a pneumatically controlled ventilator supplied with a contemporary FAM was directly proportional to V_T and inversely proportional to total thoracic compliance. These results are logical, in that the gas within the bellows canister must obey Boyle's Law. More importantly, they are clinically relevant given that knowledge of the O_2 consumption is essential for calculating the duration of a back-up O_2 cylinder should loss of central supply of compressed gases occur. For example, using data from the worst case scenario tested (LC-1000 mL lung model with a FGF of 1 L/min) the O_2 consumption rate was 15.9 L/min. Assuming an E cylinder O_2 volume of 660 L, the cylinder would be empty in <42 min. Were the likely increased FGF associated with preoxygenation and emergence also considered, the cylinder would be emptied even sooner.

The results with the pneumatically controlled ventilator compare unfavorably to those reported by Taenzer et al.[4] who tested the Narkomed 2B ventilator using a 500 mL V_T with a 3-L breathing bag as a test lung. In their study, the DG consumption was 5.57 L/min compared with a pneumatically controlled ventilator consumption of 8.3 L/min. That the Narkomed 2B ventilator consumed less O_2 was not surprising for two reasons. First, the Narkomed 2B is
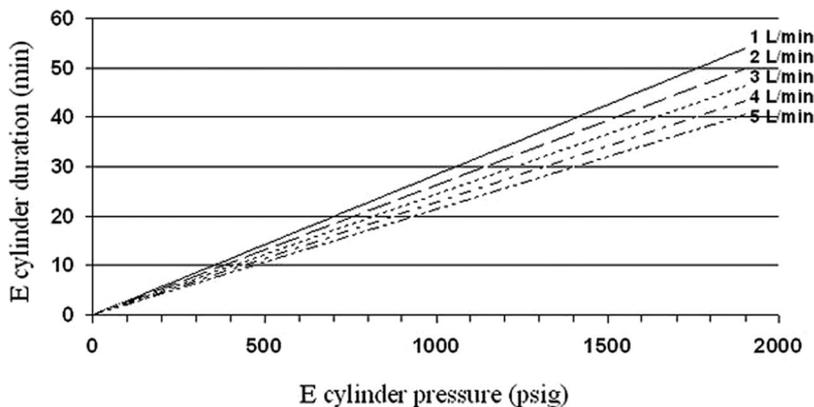
Figure 2. Estimated E cylinder duration with tidal volume (V_T) = 750 mL, fresh gas flow (FGF) = 1 to 5 L/min, and high thoracic compliance. Estimates extrapolated from data generated with the Magellan-2200 field anesthesia machine (FAM)'s pneumatically controlled ventilator with V_T = 750 mL and FGF = 1 L/min in a high thoracic compliance lung model.
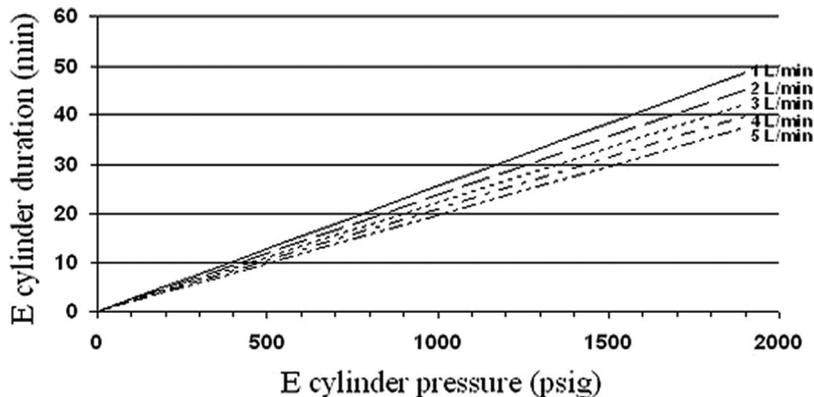

Figure 3. Estimated E cylinder duration with tidal volume (V_T) = 750 mL, FGF = 1 to 5 L/min, and low thoracic compliance. Estimates extrapolated from data generated with the Magellan-2200 FAM's pneumatically controlled ventilator with V_T = 750 mL and FGF = 1 L/min in a low thoracic compliance lung model.

an electronically controlled ventilator and has no PC gas requirement. Second, its air injector incorporates ambient air as part of the DG, reducing the compressed gas required for each breath.[7]

Taenzer et al. also studied the Ohmeda 7000 ventilator with the same lung model used in their Narkomed 2B study but with a FGF = 3 L/min. With that ventilator, the DG consumption was 5.44 L/min. Although the increased requirement with the pneumatically controlled ventilator may be attributed to its PC gas requirement, they used a greater FGF and lower compliance lung model.[3] It is uncertain how the Ohmeda 7000 ventilator's DG requirement would have compared with the pneumatically controlled ventilator under the same test conditions.

Klemenzson and Perouansky[5] studied the Ohmeda 7900 series ventilator but used a 700 mL V_T and a lung model with HC and LC settings identical to those used to test the pneumatically controlled ventilator reported here. They reported a DG consumption of 9.05 L/min which also compares favorably to the 10.6 L/min consumed by the pneumatically controlled ventilator with a slightly larger V_T = 750 mL. In the LC model, the DG consumption was positive end-expiratory pressure (PEEP) dependent. With 0 cm H_2O PEEP, the DG consumption was approximately 11.8 L/min, comparable with the pneumatically controlled ventilator. With 10 cm H_2O PEEP, it was 14.1 L/min.

A study of the Narkomed M FAM used a less sophisticated lung model.[3] Calculations using those data reveal a maximum DG consumption of 5.2 L/min. Those results compare favorably with the pneumatically controlled ventilator reported here and to the data reported by Taenzer et al.[4] using a similar ventilator. This is likely related to the Venturi effect produced by the Narkomed ventilator's air injector assembly and precise adjustment of the inspiratory flow setting that prevented an inspiratory pause, thereby, decreasing DG volume.[7]

This study of a pneumatically controlled ventilator had four main limitations. The first was that airway resistance remained constant for all groups. Patients with increased airway resistance may have DG consumption that exceeds those reported here. The second limitation was not testing the effect of PEEP on DG consumption. Patients with poor total thoracic compliance are often ventilated with PEEP, which may increase DG consumption. The third was only testing the ventilator with a RR = 10, since the compressed gas requirements may change for other RRs. The fourth was using two different technologies for measuring gas flow, i.e., Wright respirometer (spinning vane) for DG and pneumotach (differential pressure) for V_T. However, DG can be predicted by the following equation:

$$DG = V_T - FGF \times \text{inspiratory time} + C_{\text{circuit +vent}} \times \text{PIP},$$

where V_T = tidal volume (mL),

FGF = fresh gas flow (mL/s),

$C_{\text{circuit+ vent}}$ = measured compliance of circuit and ventilator bellows (5 mL/cm H_2O), and PIP = cm H_2O

Figure 4. Estimated H cylinder duration with tidal volume (V_T) = 750 mL, FGF = 1 to 5 L/min, and high thoracic compliance. Estimates extrapolated from data generated with the Magellan-2200 FAM's pneumatically controlled ventilator with V_T = 750 mL and FGF = 1 L/min in a high thoracic compliance lung model.
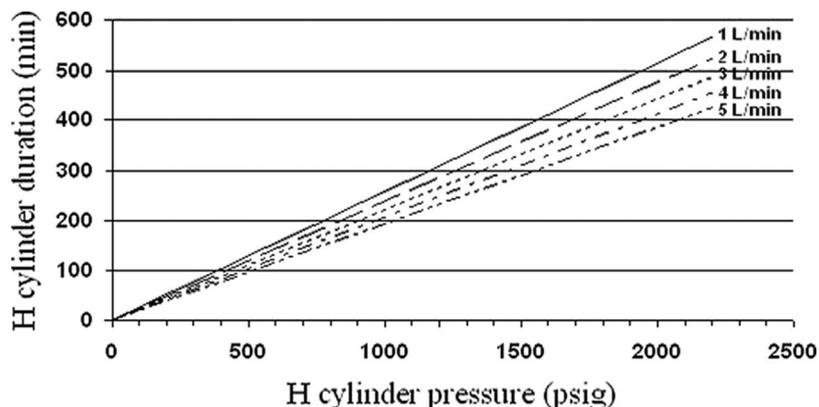
Figure 5. Estimated H cylinder duration with tidal volume (V_T) = 750 mL, FGF = 1 to 5 L/min, and low thoracic compliance. Estimates extrapolated from data generated with the Magellan-2200 FAM's pneumatically controlled ventilator with V_T = 750 mL and FGF = 1 L/min in a low thoracic compliance lung model.
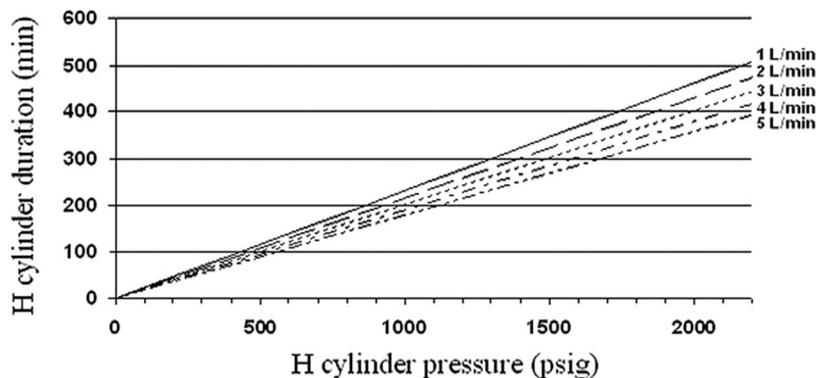
Comparing calculated DG volumes with measured DG volumes revealed a difference of 3.5% ± 2.4%, which indirectly supports the measured data.

The Magellan-2200 FAM is approved by the United States Food and Drug Administration for marketing in the United States for use in remote, hospital, and office-based settings (510(k) final decision available at http://www.fda.gov/cdrh/pdf/k010613.pdf, accessed November 9, 2007). Hence, the data reported here are clinically relevant to both military and civilian clinicians who work in these settings. Foreknowledge of a ventilator's compressed gas consumption is key to preventing hypoxic injury to patients when compressed gas is supplied by cylinders. To increase the margin of patient safety, cylinder duration should be calculated with a "worst case" lung condition (in this study, the HC-1000 mL model) that over-estimates DG consumption for a smaller V_T and/or increased compliance. To facilitate predictions of E and H cylinder duration, the data from the HC-750 and LC-750 lung models were used to generate graphs depicting approximate cylinder duration with FGF = 1 to 5 L/min (Figs. 2–5). Given that the lowest PIP in the LC groups was 29 ± 0.8 cm H_2O, it may be clinically practical to define LC as PIP ≥25 cm H_2O for the sake of cylinder duration calculations.

In conclusion, this study determined the total O_2 consumption of a pneumatically controlled ventilator in a contemporary FAM. It also determined that the PC gas requirement was approximately 4 L/min. DG volume required in this FAM ventilator is directly proportional to V_T and inversely proportional to lung compliance. Combining knowledge of the patient's total thoracic compliance and V_T with the data in Figures 2–5 facilitates prediction of compressed gas cylinder duration should a central supply of compressed medical gases be lost. Although these figures provide useful information to estimate the expected duration of a compressed gas cylinder, the actual duration will vary from the estimates when patients have airway resistance, V_T, total thoracic compliance, and/or FGF that differs from the test conditions. To maximize patient safety, it is essential to monitor the cylinder's pressure manometer in real time to determine both the cylinder depletion rate and the available compressed gas reserves.

REFERENCES

1. Chatburn R, Branson R. Classification of mechanical ventilators. In: MacIntyre N, Branson R, eds. Mechanical ventilation. Philadelphia: WB Saunders, 2001:1–50
2. Patterson JR, Russell GK, Pierson DJ, Levin DC, Nett LM, Petty TL. Evaluation of a fluidic ventilator: a new approach to mechanical ventilation. Chest 1974;66:706–11
3. Szpisjak DF, Lamb CL, Klions KD. Oxygen consumption with mechanical ventilation in a field anesthesia machine. Anesth Analg 2005;100:1713–7
4. Taenzer AH, Kovatsis PG, Raessler KL. E-cylinder-powered mechanical ventilation may adversely impact anesthetic management and efficiency. Anesth Analg 2002;95:148–50
5. Klemenzson GK, Perouansky M. Contemporary anesthesia ventilators incur a significant "oxygen cost". Can J Anaesth 2004;51:616–20
6. Dorsch JA, Dorsch SE. Anesthesia Ventilators. In: Understanding anesthesia equipment. 4th ed. Baltimore: Lippincott Williams & Wilkins, 1999:309–54
7. Cicman JH, Skibo VF, Yoder JM. Anesthesia systems. Part II: operating principles of fundamental components. J Clin Monit 1993;9:104–11