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Functional characteristics of anesthesia machines with circle breathing system

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S U M M A R Y

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Presently, the majority of anesthesia machines or workstations are ventilators that incorporate a classic circle system/circuit with a CO₂ absorber that allows rebreathing of exhaled gases. The performance characteristics of these machines are related to the physical structure of the breathing circuit. Limitations related to the classical circle breathing circuit are progressively disappearing with the arrival on the market of modern anesthesia machines with modified circular circuits, which offer a series of advantages in relation to the classic circular circuit. The present review describes the basic functional characteristics common to any anesthesia machine and that determine their clinical performance. The knowledge of these characteristics is essential for the clinical use of anesthesia machines and for analyzing their evolution.

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1. Introduction

There are some basic functional characteristics common to any anesthesia machine with a circular breathing circuit that are important to know in order to understand their clinical performance: the internal volume (with the time constant), the compressibility (or internal compliance), the resistance, the impermeability, the efficacy (coefficient of fresh gas utilization) and the composition of the inspired gas mixture.

2. Volume of the circular breathing circuit: time constant

The entire volume of a circular circuit is the sum of the volumes of all its components. In anesthesia machines with a circular circuit, internal volume determines important aspects of its clinical performance. To calculate this volume, it is necessary to know the volume of all the elements (internal and external) of the breathing circuit. These vary from one machine to other. For example, the internal volume of the Cicero anesthetic machine (Dräger Medical, Lübeck, Germany) would be calculated as the sum of two 1-m corrugated hoses going to the patient (0.9 L), the internal breathing circuit of the machine (0.6 L), the Jumbo canister for CO₂ absorption (2 L), the 2.3 L reservoir bag filled up to 75% of its maximal capacity (1.5 L), the hose connectors (0.5 L), and the internal volume of the ventilator (0.7 L); therefore, the total machine-related volume will be around 6.2 L.¹

When the composition of the fresh gas is modified, the rate at which a target composition of the inspired gas is reached depends on the internal volume of the circuit and on the magnitude of the fresh gas flow (and on anesthetic uptake). These two factors determine the time constant.² The rate at which fresh gas is mixed with exhaled gas to produce the inspiratory mixture is proportional to the internal volume of the machine and inversely proportional to the fresh gas flow. The mixing of the rebreathed gas with fresh gas is an exponential process. In general, exponential processes are characterized as decreasing in rate as the process advances. The time constant (TC) is the usual way of indicating this rate and is defined as the time required to complete the whole process if the initial rate does not change. However, due to its changing rate, the exponential phenomenon can only be considered complete when a period of time 3 times the TC has passed.³

To illustrate these concepts; imagine a barrel with a 10-L volume. If we open a faucet placed in the base of the barrel, which allows the volume to flow out at a rate of 1 l/min, it seems reasonable that it will take 10 min to empty the barrel, a value obtained by dividing the volume of the barrel by the rate of flow out of the barrel (volume/flow). However, this assumption is incorrect because the process of emptying is not linear but exponential; that is, as the barrel empties, the rate of flow from the barrel progressively decreases. The 10 min calculated above would reflect the time required to empty the barrel if the initial rate did not change over time, and is defined as the TC of this system (volume/flow). With any exponential phenomenon, after passing a period of time equivalent to 1 TC (10 min in the example above), the phenomenon is 63% complete (6.3 L have emptied); after a period of time equivalent to two TCs (20 min) it is 86% complete (8.6 L), and only

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after a period of time 3 times the TC (30 min) will the phenomenon be 95% complete and hence can be considered complete for practical purposes (although mathematically it would actually take an infinite amount of time) (Fig. 1).

To summarize, any exponential process can be considered complete after a period of time equivalent to 3 times the TC (the barrel would take $3 \times 10 \text{ min} = 30 \text{ min}$ to empty). If liquid was added to the barrel simultaneously as it empties, this factor would have to be considered because it would take more time to empty the barrel, depending on the rate of the flow into the barrel as follows: $TC = V / (\text{rate of flow out} - \text{rate of flow in})$. In circular circuits (although they do not empty but are refilled with fresh gas) the phenomenon of mixing fresh gas with the exhaled gas that occupies the volume of the circuit is exponential; therefore, it is ruled by the same principles described in the example. The time needed to reach any set change in the composition of the fresh gas is equivalent to 3 times the TC of the circuit.

In the patient attached to the system, as in the barrel example, this is calculated by dividing the entire volume of the system (volume of the circuit plus the functional residual capacity of the patient) by the setting of the fresh gas flow (FGF).² When we set the Cicero with an FGF of 2 L/min, the time constant would be: $TC = [6.2 \text{ L (circuit)} + 2.4 \text{ L (FRC)}] / 2 \text{ (L/min, FGF)} = 8.6 / 2 \text{ min} = 4.3 \text{ min}$. If we modify the mixture of N_2O/O_2 , this change would take $3 \times 4.3 \text{ min} = 12.9 \text{ min}$ to modify the FiO_2 . If we use half the FGF, the TC would be double; conversely, by doubling the FGF, the TC would be halved. Any change in gas composition would take twice or the half the time to be reached, respectively. In clinical practice, the time taken to produce such a variation is even longer than the calculated one, because of the lung's uptake of the administered gas in that moment (oxygen, or volatile or anesthetic gases). In accordance with Conway,⁴ the TC is calculated as follows:

$$TC = (V_{\text{internal}} + V_{\text{FRC}}) / (\text{FGF-uptake}).$$

In clinical practice with circular breathing circuits, to accelerate any process by shortening the TC, the solution is to transiently raise the FGF. With a Cicero (Dräger Medical) using an FGF of 6 L/min, the TC will be around 1 min, and approximately 3 min will be needed to change to the new composition of inspired gas.

2.1. Solutions to the internal volume

To reduce the internal volume, some devices mix the rebreathed gas with the fresh gas inside the ventilator itself (generator of the VT), eliminating the reservoir bag. Machines like Aespire, Advance, and Aisys, (General Electric Healthcare) eliminate the bag but have generators (bellows-in-box) that do not completely empty at end-insufflation. When the FGF is reduced, the "reserve" volume of the bellows (generator) prevents changes in VT, but the internal volume of the machine is reduced only a little, in turn improving the TC only a little. Nevertheless, in these machines, the continuous supply of fresh gas and the inlet-point for fresh gases improves their performance. The internal volume of these machines is around 2.8 L (bellows: 1.5 L; CO_2 absorber: 1 L; and internal circuit, approximately 300 mL). With an FGF of 1 L/min, the TC is around 4 min.⁵

In the Dräger Medical machines (Fabius, Primus), the generator is a piston that empties completely during inspiration, so the internal volume is only around 2.5 L (including the canister of the absorbent). Nevertheless, a bag is needed to mix the gases, which increases the internal volume. In these machines with an FGF of 1 L, the TC is around 4 min.⁶

Reducing the size of the canister to reduce the internal volume is impractical, because the CO_2 absorbent runs out after a few hours with low flows. This explains why being able to change the soda lime reservoir while the ventilator is being used is an important characteristic, and cannot be done in all machines. The Aespire, Advance, and Aisys of General Electric Healthcare (GE) have a 950-mL disposable canister filled with 850 g of soda lime that can be replaced very quickly without interrupting the ventilation.

The most definitive solution to the internal volume has been tackled from the perspective of automation. In the Zeus (Dräger Medical) machine, the FGF and inhaled anesthetic concentration settings are independent (the module is called 'direct injection of volatile agents', DIVA).⁷ The DIVA module injects the necessary volume of halogenated agent (saturated vapor) into the FGF over a short time to achieve the target end-tidal concentration (set by the anesthetist) by comparing the Et concentration setting to the continuous measurement of the actual Et concentration. For example, it is possible to increase or decrease FGF without affecting the Et concentration of the halogenated agent and vice versa, and it is possible to increase or decrease the Et concentration of the halogenated agent independently of the FGF. With this system, any modification takes place in less than 2 min (TC of less than 1 min). Working in its automatic working mode (auto-control) that automatically adjusts the minimum FGF, the TC is maintained at approximately 1 min.⁸

3. Compressibility of the circuit (internal compliance)

In anesthesia machines, during inspiration, part of the volume delivered by the generator (as adjusted VT) is compressed inside the breathing circuit and, therefore, does not reach the lungs. During exhalation both compressed volume and volume exhaled from the lungs are measured as *expired VT* by the spirometer (when it is placed at the end of the expiratory limb). This way, the loss of VT because of gas compression inside the circuit is not detected by the spirometer. The compressibility of the circuit is the parameter that characterizes the volume/pressure relationship of the machine and, therefore, indicates the volume that is compressed inside the machine for every cm of H_2O increase in pressure; this is called internal compliance of the circuit (V/P expressed in ml/cm H_2O). The net effect is that the more compressibility or more pressure at the end of the inspiration (P plateau), more of the volume is retained in the system or the more the VT is reduced.^{9,10}

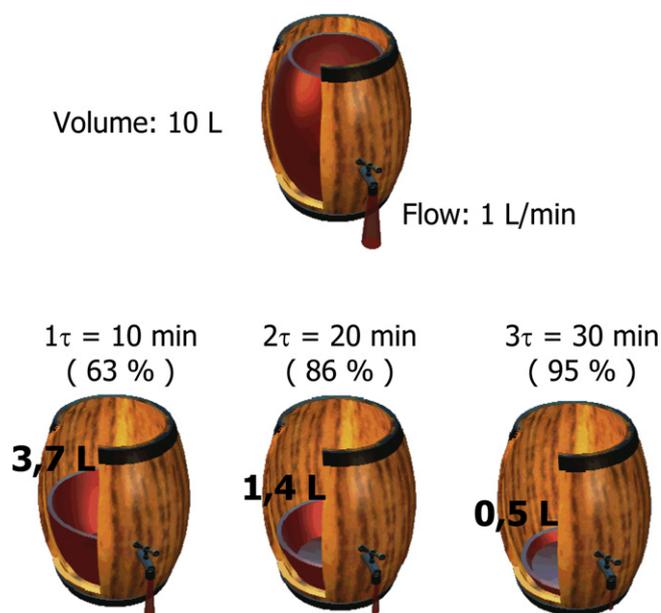


Fig. 1. Example of an exponential process (see the text). τ : time constant. (Drawing courtesy of Dr. Manuel Munoz).

In anesthesia machines, the compressibility is determined by its internal volume and by the distensibility of the components (especially the bellows). In ideal conditions, the compressibility of a 1 L volume is 1 ml for each cm of H₂O of pressure increase. Therefore, machines with an internal volume of 6 L have an internal compliance (compressibility) of at least 6 ml/cm H₂O. This means that the internal compliance is calculated by taking into account the internal volume only, and not the distensibility of some of the components. Nevertheless, during the auto-check, some machines (Fabius, Dräger Medical) offer values of compliance from 0.8 to 2 ml/cm H₂O, which is below the expected value of their internal volume. This happens because only the internal components are checked (piston and internal circuit of the machine) regardless of the external breathing circuit, absorber, bag, etc., explaining why the compliance with all these elements nears 5 ml/cm H₂O.

In case of pediatric patients, the inadvertent reduction of the delivered VT because of compression in the circuit can be remarkable. If an inspiratory pause is not used, the end inspiratory pressure (peak pressure) could be very high and the delivered VT much lower, so they could easily produce hypoventilation.¹¹ The same would happen in patients with reduced thoracic or pulmonary compliance (morbid obesity, scoliosis, laparoscopic surgery, or ARDS).¹²

3.1. Solutions to the VT decrease problem caused by compressibility

Anesthesia machines have implemented a mechanism called *compensation of the internal compliance*. In summary, during the automatic checking of the machine, there is an automatic process for calculating its compressibility (internal compliance); Let's say that for example, the machine has calculated an IC of 5 ml/cm H₂O. Knowing the IC and measuring the Ppl, compressed volume (calculated by $V_c = IC \times Ppl$) is added to the VT to adjust the actual VT delivered to the patient to the VT setting. The mechanism of compensation does not eliminate the internal compliance, but avoids reduction of VT caused by compression. This compensation obviously does not modify the internal volume of the circuit and, therefore, does not affect its TC. Not all anesthesia machines are the same, and of those that do compensate, the mechanism for this compensation may be different.

There are machines in which the generator is an electrically-driven piston (Fabius, Primus, Dräger Medical) that empties completely with the insufflation of the VT. In these machines, the mechanism of compensation is very precise; a simple measurement of the inspiratory pressure allows the additional volume needed to compensate for the compressed volume to be calculated. The precision of the VT adjustment is around $\pm 5\%$, or a little more when a VT is adjusted below 200 mL.^{6,13}

When the generator is a bellows compressed by a driving external gas (Aestiva, Aespire, Advance, and Aisys, GE), the bellows do not completely empty during inspiration. The residual volume in the bellows is variable; therefore, the compressed volume is variable. Because of this, in the 7900 series of ventilators and in the Advance, compliance is compensated for in a particular way (in the series 7100, this compensation is optional). This consists of measuring the inspired volume with a flow sensor placed in the inspiratory limb and comparing this value with the VT setting for delivering the difference during the same inspiration. Simultaneously, a flow sensor is added to the expiratory limb to verify that the actual volume that the patient exhales equals the VT settings. This double system of measurement of flow to compensate for the compliance has been named Duo-flow. The precision of the VT delivered is around $\pm 10\%$ or better for VT settings below 200 mL, and 15% for VT settings below 60 mL.⁵

The most recent solution is related to the use of machines with a turbine generator (Zeus, Dräger Medical). In these machines, exhaled gas and fresh gas are mixed inside the circuit, where a turbine pushes the gas mixture into the lung. The volume occupied by the turbine is small, constant, and does not retain any gas. Also, an external reservoir bag is not necessary because the gas is mixed inside the system. Therefore, the IC is constant and easy to compensate by just measuring inspiratory Ppl. Also, it incorporates a flow sensor at the Y-piece, which informs the system about the delivered volume to fit it to the one it is set for. The velocity of compensation in the same respiratory cycle is much higher than with other systems because of the rotation speed of the turbine, and the precision of the VT is better than 5%.⁶

4. Resistance of the circuit

Internal Resistance of the circuit is defined as the minimum pressure that allows the circulation of gas flow. Anesthesia machines have several resistive components. A starting point is to understand that any circular circuit needs a leakage valve for excess gas (air pressure liberation valve [APL]) because the FGF is higher than the patient's uptake. In circular circuits, this valve should be closed at the end of the expiration so the exhaled gases can re-circulate. From this moment, when the gas (mixture of fresh and exhaled gases) has accumulated in the circuit and the pressure increases, the valve opens, and the excess gas leaks out. The pressure needed to open the valve is the PEEP observed in the anesthesia machines, and usually approximately 2–4 cm H₂O. This residual pressure is the minimal resistance of the circuit. In general, this PEEP is a little higher when the FGF is very high.¹⁴ In clinical practice, this PEEP, which can be called *non wished* or *non adjusted*, may not be important (it even can be beneficial), but it usually confounds the anesthesiologist who has not adjusted any PEEP.

A second component is the frictional resistance or flow resistance, which depends on the internal diameter and the disposition of the components in the internal breathing circuit as well as the gas flow rate.¹⁴ In summary, smaller diameters (radius), greater numbers of bends in the circuit (turbulence), and higher inspiratory and expiratory gas flow can all generate greater resistance.

The European normative EN 740: 1999,¹⁵ requires the inspiratory and expiratory resistances to be less than 6 cm H₂O (measured at a flow of 60 L/min).

Resistance is very important for spontaneous ventilation through the breathing circuit. The expiratory resistance must not limit the free exit of the exhaled gas; otherwise, dynamic PEEP will be generated. On the other hand, inspiratory resistance must be as low as possible to minimize the respiratory work-load during spontaneous inspiration¹⁶ or to minimize trigger effort when assisted supports are used (pressure support ventilation).¹⁷

A third resistance is the PEEP valve itself, which is an adjustable resistance deliberately set for applying a residual pressure at the end of the expiration.

4.1. Solutions to the resistance problem

All anesthesia devices on the market have an internal resistance below that accepted by the European normative. However, the circuit structure and APL valve determine the minimal *non adjusted* PEEP and its dependence on FGF; hence, PEEP changes from one machine to another. Some machines have a minimal PEEP of 2 (Fabius, Dräger Medical) or less (Primus, Dräger Medical), and are not affected by the FGF. Others have a PEEP that is 3–4 cm H₂O and are influenced more by the FGF (Aespire, Advance, Aisys, GE). In the Zeus (Dräger Medical), working with a continuously rotating turbine, a PEEP of 3 cm/H₂O is generated.

Inspiratory resistance, which is essential while on assisted ventilatory modes (pressure supports), is minimized by using very sensitive trigger systems (Primus, Dräger Medical). However, it improves even more with a flow trigger using a flow-by system (Aestiva, Advance, GE and Zeus, Dräger Medical). This system consists of a bias flow (adjustable from 0.2 to 1.0 L/min) that circulates continuously inside the circuit, and available to the patient at the same time as the inspiratory trigger.¹⁸ The sensitivity in the Zeus has improved even more since the flow sensor is located at the Y-piece, very near the patient.⁶

Finally, the functioning of the PEEP valve is a fundamental element of a good anesthesia machine. In general, the PEEP valves are adjustable springs with which expiratory flow is not significantly altered. Nevertheless, only in the machines with electronically-driven mechanical PEEP valves (Fabius, Zeus, Dräger Medical and Advance, Aisys GE) is exhalation not limited and independent of the PEEP level. The PEEP setting is very exact and not modified by respiratory frequency or FGF.

5. Impermeability of the breathing circuit

The anesthetic circuits, when pressurized during MV, are not perfectly sealed because of the large number of components. Common sources of leakage are the connections and the APL valve. The quantity of gas lost depends on the importance of the leaking orifice and the pressure in the anesthetic circuit. In spontaneous ventilation, leakage does not modify the VT significantly but changes the gas composition. Nevertheless, in controlled ventilation, leakage increases as the inspiratory pressure (peak and plateau pressure) increases, and with greater PEEP.¹⁹ Leakage less than 200 ml/min at 30 cm H₂O of pressure is not important.²⁰ The European norm, EN 740 requires, for example, that leakage across the APL valve, when it is completely closed, should not exceed 50 ml/min.²¹

In the literature, many reports have described problems in ventilation during anesthesia caused by leaks.^{22,23,24} When a leak is suspected, it is necessary to continue the algorithm of low pressure proposed by Raphael.²⁵

5.1. Solutions to the problem of leaks

Modern circular circuits have faced the problem of the leaks from a dual perspective. First, the external connectors; the classic external block, usually attached to the machine, which includes valves, reservoir, canister etc, tends to be eliminated. These are still present in some machines (Fabius, Dräger Medical) or concealed in others (Aestiva, GE), but as an external block they are almost completely (Primus, Dräger Medical and Advance, GE) or completely (Zeus, Dräger Medical) eliminated in most modern machines. Other workstations without external blocks (Aespire, Aisys, GE) have multiple necessary internal connections that can be disassembled to facilitate autoclave sterilization. A weakness of an anesthesia machine is the number of its external (or/and internal) connections, because it increases the number of components that have to be evaluated for possible leaks (and disconnections).^{26,27}

The second approach to leaks is the automatic quantification of the leaks by the machine during the initial auto-check process, comparing the value obtained with a predefined value of tolerable leakage. If the leak is excessive, a message appears on the monitor screen and, in some cases, will prevent the device from functioning (Dräger Medical). In GE machines, the user can choose whether or not to verify minor leaks greater than 250 ml. In any case, the presence of leakage does not prevent ventilation from being initiated.

6. Composition of the inspired gas mixture

In a circular breathing circuit, the composition of the inspired gas that is delivered to the lung can be practically identical to the fresh gas (adjusted in the flowmeters) or it can be much different. Five factors determine the composition of the inspired gas; (1) flow rate and composition of the fresh gas, (2) rebreathing, (3) adsorption, and absorption of the anesthetic gases by the rubber/plastic elements of the anesthetic circuit, (4) gas leaks, and (5) in spontaneous ventilation, the entrance of ambient air. The details of each factor can be found in other publications.^{28,29}

In a circular circuit, fresh gas is diluted in the rebreathed gas; hence, of the above-mentioned factors, FGF and rebreathing play a determinant role in the composition of inspired gas. With greater FGF and less reinhalation, the composition of the inspired gas is more similar to the fresh gas; but with lower FGF and greater rebreathing, the difference between the composition of the inspired gas and the fresh gas will be greater.³⁰ This effect depends on the coefficient of utilization of the fresh gas (FGU or *efficacy*) of the circuit for using fresh gas (see below). On the other hand, it is necessary to point out that the most frequent cause of changes in the composition of the inspired gas are leaks, the effect of which obviously depends on the magnitude of the leak.

6.1. Solutions to problems with the composition of the inspired gas

The first solution currently demanded in the Norm EN 7140 from 1999 for machines with circular circuits is the precise monitoring of the fraction of inspired oxygen, and the impossibility of delivering hypoxic mixtures. These characteristics are guaranteed with the CE mark of the machine, and are described in detail elsewhere.²¹ On the other hand, it is necessary to point out that the incorporation of electronic flowmeters does not affect the effect of gas dilution *per se*. It also does not affect having two separate controls for adjusting the FGF (in liters/minute) and FiO₂ (in %) (Primus, Dräger Medical; Advance, GE). With these controls, the mixture of fresh gas is adjusted exactly, but the effect of diluting the inspired gas related to the magnitude of the FGF is not avoided. The only mechanism that really avoids this effect, using an electronic flowmeter and blender, is the incorporation of a system of measuring the composition of the inspired gas and the automatic readjustment of the fresh gas flow, to accurately deliver the set mixture (Zeus, Dräger Medical).^{6,7} Finally, leakage autochecks with a low tolerance level accepted by the machine might also be considered to be an indirect mechanism of guaranteeing the composition of the inspired gas.

7. Efficacy of the circuit: coefficient of fresh gas utilization (FGU)

The coefficient of fresh gas utilization (FGU) of a circular breathing circuit is defined as the relationship between the volume of fresh gas that enters the lungs with respect to the entire volume of fresh gas that enters the circuit. The efficacy would be the expression in percentage of this coefficient. In an ideal circuit (in which the coefficient equals 1 and the efficacy is 100%), all the fresh gas (FGF) would go to the lungs, and the excess gas (difference between VE and FGF) that is eliminated through the APL valve would be composed exclusively of exhaled gas. Nevertheless, with the circular circuits used presently, the FGU is minor. Part of the FGF goes directly to the ambient air without having passed through the lungs. Simultaneously, part of the exhaled gas (with lower oxygen concentration and higher CO₂ concentration) dilutes the fresh gas and consumes the CO₂ absorbent.

The factors that affect efficacy are, principally, the position of the inlet of the FGF (fresh gas supply) in the circuit, and the position

and functioning of the APL valve.³¹ The majority of currently used circular circuits have efficacies greater than 95% (coef. FGU: 0.95) when used with an FGF of 1 L/min. Nevertheless, with an FGF of 6 L/min, the percentage of FGF that goes to the lungs might be decreased to 50% depending on the machine.^{1,32} In any case, most machines have the highest efficacy at low fresh flow rates.³³

The lack of efficacy is not visible in clinical practice because its principal effect is to generate a lower Fi of gas, which can be attributed to the dilution effect of the inspired gases (see above). A reduced FGU with high FGF is demonstrated in clinical practice, when, with CO₂ rebreathing (exhaustion of the absorbent), the FGF is increased above the minute volume, and some reinhalation of CO₂ is still observed. This indicates that the whole FGF does not go to the lungs.³⁴

7.1. Solutions to the problem of the efficacy

In general, in all machines, the efficacy of the circuit improves when low FGF rates are used. Therefore, it is only a real problem when an FGF above 1 l/min is used. For the user of low or minimal flows, the problem is almost negligible. Based on this result, the efficacy is improved by modifying the structure and location of the components in the circuit. Automatic control of the concentration of the inspired gas simultaneously compensates for the effect of dilution of fresh gases and the efficacy.³⁵

8. Summary and conclusions

Overall, it can be concluded that it is important to know the functional characteristics of the breathing circuits, because this determines the performance of the anesthesia machines in clinical practice. The minimum requirements for the functional characteristics of an anesthesia machine today are (1) a low time constant with low flows, (2) a compliance compensation system that allows ventilation with a VT between 200 and 700 ml with an accuracy greater than 10%, (3) minimal inspiratory and expiratory resistance that generate a negligible PEEP and are compensated for by a sensitive trigger that facilitates the spontaneous ventilation and the use of assisted ventilatory modes (PSV), (4) an electronic PEEP valve, and (5) an electronic flowmeter and blender system that allow, separately, adjustment of the FGF and the concentration of inspired gases (making the effect of the dilution of inspired gases and the efficacy negligible). Unfortunately, only a very few studies have tried to compare the characteristics of the different anesthesia machines.^{36,37,38} Automation is valuable but it will never completely replace the anesthesiologist's knowledge of the basic functional characteristics of the anesthesia machines.³⁹

Conflict of interest statement

None.

References

- Baum JA. Technical requirements for anaesthesia management with reduced fresh gas flow. In: Baum JA, editor. *Low flow anaesthesia*. 2nd ed. Oxford: Butterworth; 2001. 111–173.
- Baum JA. Control of inhalational anaesthesia. In: Baum JA, editor. *Low flow anaesthesia*. 2nd ed. Oxford: Butterworth; 2001. 73–87.
- Dolenska S. Exponentials 2: properties of exponential decay curve. In: Dolenska S, editor. *Basic science for anaesthetists*. Cambridge: Cambridge University Press; 2006. 36–39.
- Conway CM. Closed and low flow systems. Theoretical considerations. *Acta Anaesthesiol Belg* 1984;**34**:257–63.
- Healthcare GE. *Technical specifications brochure*, www.gehealthcare.com; 2008.
- Dräger Medical. *Technical specifications brochure Fabius GS*. Primus, www.Draeger.com; 2008.
- Meyer JU, Kullik G, Wruck N, Kück K, Manigel J. Advanced technologies and devices for inhalational anesthetic drug dosing. In: *Modern anaesthetics (handbook of experimental pharmacology series)*. Berlin: Springer; 2008. 451–470.
- Struys MM, Kalmar AF, De Baerdemaeker LEC, Mortier EP, Rolly G, Manigel J, et al. Time course of inhaled anaesthetic drug delivery using a new multifunctional closed-circuit anaesthesia ventilator. In vitro comparison with a classical anaesthesia machine. *Br J Anaesth* 2005;**94**:306–17.
- Otteni JC, Ancellin J, Cazalaà JB, Clergue F, Feiss P, Fougère S, et al. Appareils d'anesthésie. modes disponibles en France. critères de choix. *Ann Fr Anesth Reanim* 1995;**14**:13–28.
- Dorsch JA, Dorsch SE. The breathing system: general principles, common components and classifications. In: Dorsch JA, Dorsch SE, editors. *Understanding anaesthesia equipment*. 3th ed. Baltimore: Williams and Wilkins; 1994. 149–165.
- Bachiller PR, McDonough JM, Feldman JM. Do new anaesthesia ventilators deliver small tidal volumes accurately during volume-controlled ventilation? *Anesth Analg* 2008;**106**:1392–400.
- Soro M, De Andrés J, Navarro R, Belda FJ, Cortés Uribe A. Influence of internal compliance of the anaesthetic circuit on the reduction of lung compliance during laparoscopic cholecystectomy. *Br J Anaesth* 1997;**78**(Suppl. 1):A 157.
- Dräger Medical. *The anaesthesia ventilator. why is the piston replacing the bellows? draeger brochure*, www.Draeger.com; 2007.
- Martin DG, Kong KL, Lewis GT. Resistance to airflow in anaesthetic breathing systems. *Br J Anaesth* 1989;**62**:456–61.
- Baum J. Patient safety aspects of low flow anaesthesia. In: Baum J, editor. *Low flow anaesthesia*. 2nd ed. Oxford: Butterworth; 2001. 191–214.
- Agilar G, Soro M, Belda FJ, Guillén A, Juste J, Martí F. Additional work of breathing for different circuits in anesthetized spontaneous breathing patients. *Anesth Analg* 2001;**92**:S312.
- Aguilar G, Jover JL, Soro M, Belda FJ, Garcia-Raimundo M, Maruenda A. Additional work of breathing and breathing pattern in spontaneously breathing patients during pressure support ventilation, automatic tube compensation and amplified spontaneous pattern breathing. *Eur J Anaesthesiol* 2005;**22**:312–4.
- Ferreira JC, Chipman DW, Kacmarek RM. Trigger performance of mid-level ICU mechanical ventilators during assisted ventilation: a bench study. *Intensive Care Med* 2008;**34**:1669–75.
- Ruben H, Johansen SH. Factors influencing gas loss through leaks in anaesthetic circuits. *Acta Anaesthesiol Scand* 1967;**11**:291–5.
- Leuenberger M, Feigenwinter P, Zbinden AM. Gas leakage in eight anaesthesia circle systems. *Eur J Anaesthesiol* 1992;**9**:121–7.
- European Committee for Standardization. *Anaesthetic workstations and their modules. Particular requirements*. Brussels: European Standard EN 740; June 1999.
- Gunter JB, Myers T, Win ST, Ball J. Catastrophic failure of Aestiva 3000 absorber manifold. (*letter*) *Anesthesiology* 2004;**100**:199–200.
- Gravenstein D, Wilkhu H, Liem EB, Tilman S, Lampotang S. Aestiva ventilation mode selector switch failures. *Anesth Analg* 2007;**104**:860–2.
- Lampotang S, Sanchez JC, Chen BX, Gravenstein N. The effect of a bellows leak in an Ohmeda 7810 ventilator on room contamination, inspired oxygen, airway pressure, and tidal volume. *Anesth Analg* 2005;**101**:151–4.
- Raphael DT, Weller RS, Doran DJ. A response algorithm for the low-pressure alarm condition. *Anesth Analg* 1988;**67**:876–83.
- Brockwell RC, Andrews JJ. Complications of inhaled anaesthesia delivery systems. *Anesthesiol Clin North America* 2002;**20**(3):539–54.
- Ortega R, Zambricki ER. Fresh gas decoupling valve failure precludes mechanical ventilation in a Dräger Fabius GS anaesthesia machine. *Anesth Analg* 2007;**104**:1000–1.
- Otteni JC, Steib A, Galani M, Freys G. Appareils d'anesthésie: systèmes anesthésiques, *Encycl. Méd. Chir. Anesthésie-Réanimation*. Paris: Editions Techniques; 1994. 36-100-B-30.
- Andrews JJ. Inhaled anaesthetic delivery systems. In: Miller RD, editor. *Anesthesia*. 4th ed. New York: Churchill Livingstone; 1994. 185–224.
- Mushin WW, Jones PL. Circuitos respiratorios anestésicos. In: Mushin WW, Jones PL, editors. *Física para anestésistas*. Barcelona: Doyma; 1990. 308–333.
- Zbinden AM, Feigenbinter P, Huttmacher M. Fresh gas utilization of eight circle systems. *Br J Anaesth* 1991;**67**:492–9.
- Al-Shaikh B, Stacey S. Humidification and filtration. In: Al-Shaikh B, Stacey S, editors. *Essentials of anaesthetic equipment*. 3th ed. Edinburgh: Elsevier; 2007. 121–130.
- Baum J. Advantages of the rebreathing technique in anaesthesia. In: Baum JA, editor. *Low flow anaesthesia*. 2nd ed. Oxford: Butterworth; 2001. 88–110.
- Fernandez Rosado B, Bonome C, Belda J, Alvarez Refojo F, Rodriguez RA, Pose P. Influencia en la variación de la relación volumen minuto/flujo de gas fresco en la eficacia del circuito circular Dräger-Cicero. *Rev Esp Anestesiología Reanim*; 1999:124–8.
- Schober P, Loer SA. An innovative anaesthesia machine: the closed system. *Curr Opin Anaesthesiol* 2005;**18**:640–4.
- Liu N, Beydon L, Bach B, Bonnet F, Clergue F, Fougère S, et al. Etude de 11 ventilateurs d'anesthésie: banc d'essai. *Ann Fr Anesth Reanim* 1992;**11**:502–8.
- Odin I, Nathan N. What are the changes in paediatric anaesthesia practice afforded by new anaesthetic ventilators? *Ann Fr Anesth Reanim* 2006;**25**:417–23.
- Jaber S, Langlais N, Fumagalli B, Cornec S, Beydon L, Harf A, et al. Performance studies of 6 new anaesthesia ventilators: bench tests. *Ann Fr Anesth Reanim* 2000;**19**:16–22.
- Hogan TS. Automaticity as a cause of anaesthesia machine operator error. *Anaesthesia* 2008;**63**:680.