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FOCUS ON: MECHANICAL VENTILATION IN THE OR

Functional characteristics of anesthesia machines with circle breathing system

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SUMMARY

Presently, the majority of anesthesia machines or workstations are ventilators that incorporate a classic circle system/circuit with a CO_2 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.

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 CO_2 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 3×10 min $= 30$ 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/(rate of flow out minus the 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 L (circuit) + 2.4 L (FRC)]/2 (L/min, FGF)] = 8.6/2 min = 4.3 min. If we modify the mixture of N_2O/O_2, this change would take 3×4.3 min = 12.9 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 = (Vinternal + VFRC)/(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.

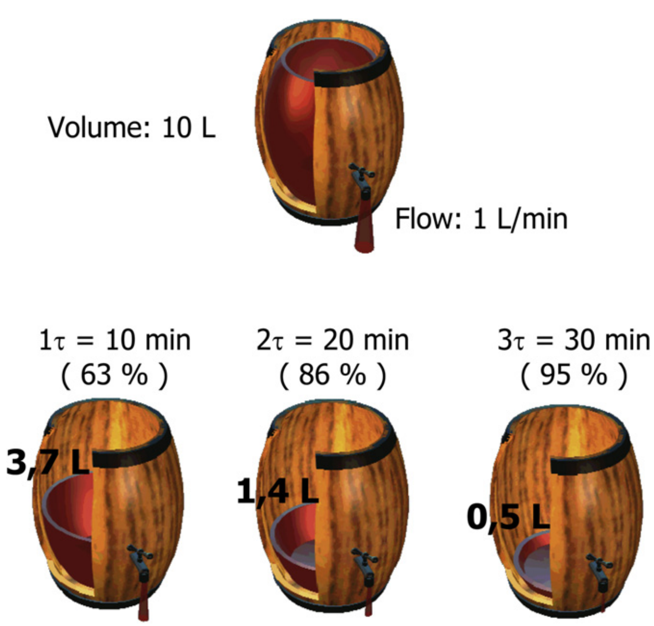

Fig. 1. Example of an exponential process (see the text). τ: time constant. (Drawing courtesy of Dr. Manuel Munoz).

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 cansiter 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]