Functions of anesthesia reservoir bag in a breathing system

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Abstract

This article addresses the different functions of anaesthesia reservoir bag in a circle anesthesia breathing system. A main purpose of the contribution was to explain complex interaction between the reservoir bag and fresh gas flow during mechanical ventilation. The anesthesia reservoir bag is a collapsible gas container which is an essential component of most anesthesia breathing system. The anesthesia reservoir bag permits manual ventilation and acts as a visual or tactile indicator of spontaneous breathing. The bag was excluded from traditional breathing system when the mechanical ventilator was in use. Discrepancies between the set and actual tidal volume can occur. However, on some anaesthesia workstation systems, such as the Dräger Primus, the reservoir bag is an integral part of the breathing system during mechanical ventilation, where it serves as a reservoir for oxygen and anaesthetic gases. In mechanically ventilated patients, gases enter the reservoir bag from the fresh gas flow during inspiratory phase, when the decoupling valve closes. The safe administration of general anaesthesia requires understanding of the technological advances in highly sophisticated anaesthetic equipment.

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1. Introduction

The anaesthesia reservoir bag is an important component in most breathing systems used in anaesthesia. Figure 1 presents a traditional or classical circle anaesthesia breathing system that comprises 7 different components:

- inflow of fresh gases,
- inspiratory and expiratory unidirectional valve;
- an inspiratory and expiratory corrugated tubes (limbs)
- Y-piece;
- adjustable pressure-limiting valve
- CO2 absorber with absorbent;
- reservoir bag (1-2).

The reservoir bag is most often placed between the expiratory valve and CO_2 absorber. Such a configuration allows for the dust from absorbent beads to be pushed into the inspiratory limb during manual or mechanical ventilation (3).

As seen in Figure 1, the inflow of fresh gases at inspiratory phase is directed to the patient through the inspiratory valve, the inspiratory limb (tube) and the Y-piece. Expired air containing carbon dioxide (CO_2) flows through the expiratory limb through the expiratory valve and fills the reservoir bag. When the pressure in the bag increases

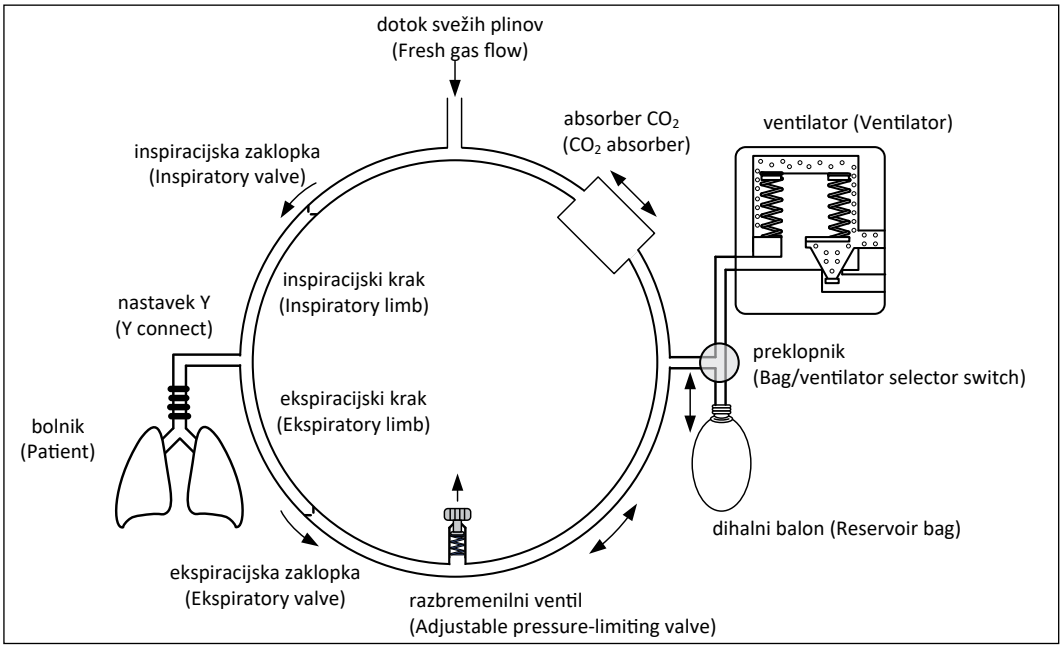

Figure 1: Traditional anaesthesia breathing system.

above the value set on the pressure-limiting valve, the respiratory gases are released from the breathing system through this pressure-limiting valve into the scavenging system. On expiration, the respiratory gases fill the reservoir bag, and on inspiration these gases return to the patient from the reservoir bag, thereby passing through the CO2 absorber, which absorbs carbon dioxide (CO2). The valves direct the circular one-way flow of respiratory gases (4). In contrast to the presented traditional Circle-breathing system, different manufacturers may have individual components placed differently.

The disadvantage of the circular breathing system is in a large number of different components where malfunctions can occur (5). These occur due to incorrectly connected connection sites, leakage of gas, obstruction of the tube, cracks in the filters, or because the tube may accidentally slip off the coupling. When connecting the tube, it is necessary to keep in mind that the tube should be pushed and rotated (the manufacturer in the user manual talks about the "push and twist" procedure). In this case the tube is attached with greater force and thus less likely to slip off.

ISO 5362 is the international ISO standard that defines the characteristics of anaesthetic reservoir bags ISO 5362:2006 – Anaesthetic reservoir bags) (7). In accordance with this standard, the maximum permissible gas leakage in reservoir bags of original nominal volume of 1 l is 10 ml/min. In reservoir bags with a volume of more than 1 l, the maximum permissible gas leakage is 25 ml/min. The leakage is measured at a pressure of 3 ± 0.3 *kPa*. Reservoirs can be made of natural rubber and contain latex (often reusable) or are made of latex-free materials and are disposable (the note that the reservoir is latex-free should be indicated on the packaging). The force that the reservoir is required to withstand during the linear load testing of the reservoir neck is 40 ± 4 *N* (7). The tolerances for the nominal volume range within ± 15 %. Connection to the breathing system is made by means of two connectors with internal diameters of 15 mm (15F, female conical fitting) and 22 mm (22F, female conical fitting). The material of the reservoir must be antistatic (i.e. not prone

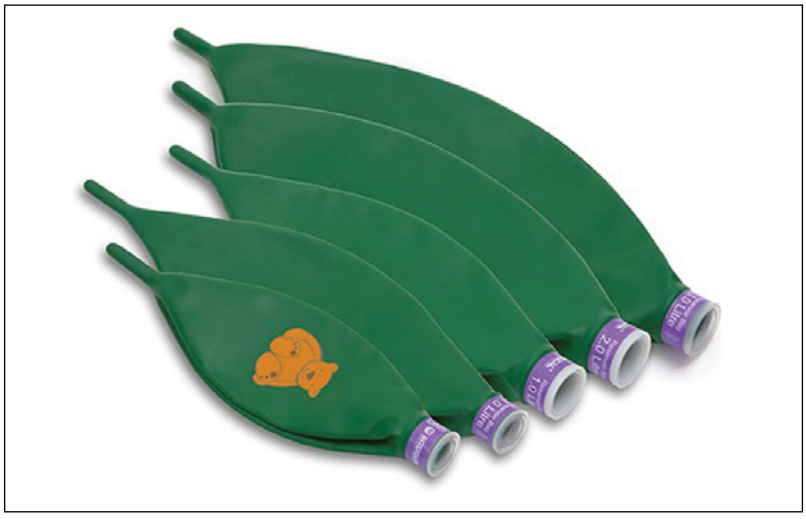

Figure 2: Breathing reservoir bags of different volumes and couplings (Intersurgical Ltd).

to static electricity buildup) and should not slip when held in hands. The material should also not be permeable to inspiration anaesthetics and should not absorb or adsorb them. The upper part of the reservoir with the coupling is called the "neck" and the opposite part is the "tail". The tail, which is a tubular extension of the reservoir, must be at least 2 cm long. When open (i.e. open tail), it functions as a relief mechanism in the linear *Mapleson F* breathing system. The reservoir bag has an ellipsoid shape, which facilitates grip (7).

Reservoir bags intended for paediatric use generally have a nominal volune of 0.5 or 1 litre (Figure 2, three lower reservoir bags), and for adults a volume of 2 or 3 l (two upper reservoir bags in Figure 2). The lower two reservoir bags in Figure 2 have couplings with a standardised internal diameter of 15 mm (15F) while other reservoir bags have a standardised internal diameter of 22 mm (22F).

In the traditional circle breathing system, a reservoir bag has a function only in spontaneous breathing or in manual positive pressure ventilation. During mechanical ventilation, it is excluded from the breathing system by bag/ventilator selector switch (Figure 1) and in this mode it has no function. The respiration function is then taken over by a mechanical ventilator.

2. Reservoir bag and spontaneous breathing

The most important function of a reservoir bag during patient's spontaneous breathing is the collection of respiratory gases. In the patient's inspiration of 500 ml of gas for 1 second, a high average flow of 30 l/min (0.5 l × 60 s) is generated; the maximum values in the middle of inspiration are higher by 30–40 % (12). The inflow of fresh gases does not allow for such high flows, so the gasses must be collected in a respiratory reservoir bag. During spontaneous breathing, the patient inhales fresh respiratory gases along with gases from the reservoir bag, which are devoid of CO_2 as they pass through the CO_2 absorber and the inspiratory valve, with the expiratory limb being closed via the expiratory one-way valve. During expiration, the reservoir bag is filled with exhaled air and the inflow of fresh gases as the inspiratory valve is closed (Figure 1). When the reservoir bag is filled up to its nominal volume, the excess gases are released through the adjustable pressure-limiting valve. In this case, the pressure limiting outflow valve in the Dräger Primus anaesthesia workstation is in the position marked "Spont" (fully open valve).

During spontaneous breathing, the reservoir bag is a visual monitor; it is slightly deflated on inspiration and refilled on expiration. The reservoir bag is also a tactile monitor, as its soft structure enables us to feel its filling or emptying by touch (23).

The monitoring of spontaneous breathing depends on several factors: the shape of the reservoir bag, its size, the

Figure 3: A protective cage on the inside of the 22F coupling.

level of inflation, the flow of fresh gases, and the patient's respiratory capacity.

The accurate assessment of the patient's respiratory volume cannot be done simply by observing the reservoir bag (8). This can provide only a rough estimate of the respiratory volume (12).

On the neck of the reservoir bag, at the site of the tube connection, there is a special plastic cage (Figure 3), which prevents that the upward turned and folded reservoir bag would clog up the connector and thus prevent gas filling.

3. Reservoir bag and manual ventilation

During manually controlled or assisted ventilation, the reservoir bag is pressed to create pressure in the circle breathing system, which results in the flow of respiratory gases from the reservoir bag to the patient. In this ventilation mode, the adjustable pressure limiting valve is only partly closed to provide the pressure required for efficient ventilation. During inspiration and expiration, the excess gas is discharged through the adjustable pressure limiting valve (the pressure in the breathing system is then higher than the pressure set on the adjustable pressure limiting valve). The pattern of gas flow direction is similar to that of spontaneous breathing. In assisted ventilation, the onset of inspiratory phase can be determined by tactile or visual monitoring of the reservoir bag.

4. Safety pressure

The reservoir bag has a safety function which protects the patient's lung from barotrauma. It is the most flexible part of the breathing system. During gas filling, it is the reservoir bag that first shows evidence of filling. When the pressure limiting outflow valve is closed, the reservoir bag is filled beyond the nominal volume, but nevertheless it must maintain a safety pressure within the limits below 60 cm H_2O (7). Laplace's law shows the correlation between the tension on the surface of the reservoir bag (T), the inside pressure (P) and the reservoir bag's diameter (r). Mathematically, it can be presented with the following equations (9-11):

$$T = \frac{P \cdot r}{2}; \qquad P = \frac{2 \cdot T}{r};$$

When the reservoir bag is filled with respiratory gases over the nominal volume, the pressure inside it starts to increase. Pressure rising (unit of force per surface:N/m^2) is counteracted by the opposite force, called surface tension or tension of the reservoir bag's wall and is expressed as unit of force per length (N/m).

Figure 4 shows how the reservoir bag has been inflated over the nominal volume with a fully closed pressure limiting outflow valve (70 cm H_2O). During inflation, the radius (r) of the reservoir bag increases along with the surface tension (T), while the pressure remains constant, as can be seen from the Laplace's law equation. In this case, the pressure measured in the Dräger Primus work station amounted to 34 cm H_2O. Prior to the experiment, we slightly stretched

Figure 4: Reservoir bag's safety function – the maintenance of a constant pressure in the respiratory system (example in the figure: pressure inside the reservoir bag: 34 cm H_2O, diameter: 66 cm, volume: 150 litres).

the Intersurgical's reservoir bag, so that we inflated it to several times its nominal volume (2 l). Before the reservoir bag burst its diameter extended to 66 cm, which corresponded to a volume of approximately 150 litres.

In establishing compliance with ISO 5362 standard, a reservoir bag is filled with water at four times the nominal value. At this experiment, the pressure should not be lower than 3 kPa = 30 hPa (approximately 30 cm H_2O) and neither higher than 6 kPa = 60 hPa (approximately 60 cm H_2O). When filling a reservoir bag with air, two times the nominal value is used. The same pressure limits are required (between 3 kPa and 6 kPa) (7). Figure 5 shows the approximate course of pressure change in the reservoir bag when it is being filled with anaesthetic respiratory gases (12-13). The curve is divided into three phases. In the first phase we observe the initial filling up to the nominal value (2 l) with only a slight increase in pressure. When the volume reaches the nominal volume, the pressure starts to increase rapidly and soon achieves the maximum value (small radius of the reservoir bag, high pressure). In the third phase that follows, the pressure reaches a plateau and is relatively constant. After an initial high pressure, all reservoir bags undergo pressure release after 1–5 seconds (13). This pressure that protects (the lungs) against barotrauma must not exceed 40–50 cm H_2O (14). The reservoir bag bursts when the surface tension is too high for the material to withstand it. Physical characteristics of reservoir bags slightly differ among producers (13). Some achieve high initial pressure values (Figure 5, curve a), others are more flexible and therefore the pressures are lower (Figure 5, curve b). The reservoir bag however does not meet the standard if it does not reach the minimum required pressure of 30 cm H_2O (Figure 5, curve c).

Modern anaesthesia workstations have an extra safety automatic mechanism against barotrauma in manual operation. The Dräger Primus anaesthesia workstation activates an alarm of the highest priority (pressure high) if on continuous inflation of the reservoir bag, the pressure set as the upper limit for alarm by the user is exceeded (15). If the pressure is below the upper level of alarm, this triggers an alarm of continuous pressure that also represents the highest priority (red colour), thus requiring immediate action. Accord-

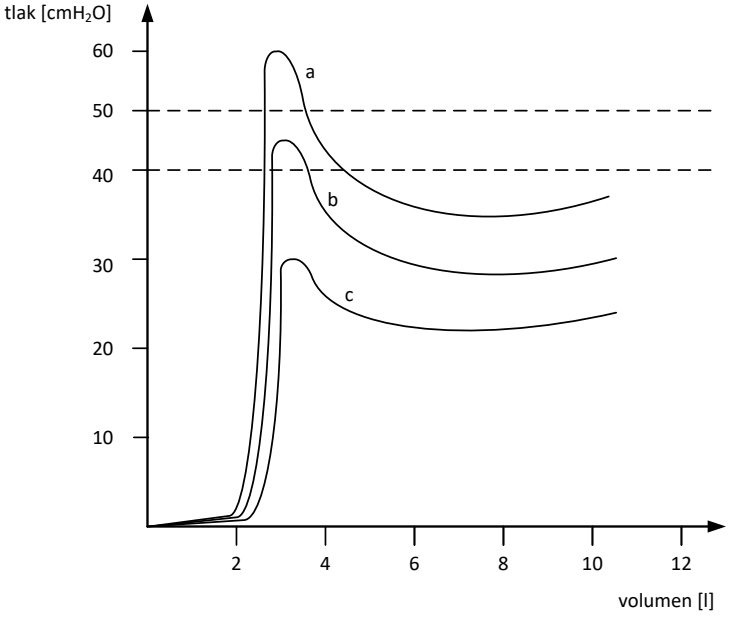

Figure 5: The course of pressure in filling reservoir bags with different levels of flexibility. The most flexible one (C) does not reach the required pressure as that with low material flexibility (a). Generally reservoir bags do not exceed the pressure within the range of 40to 50 cm H_2O). (Source: adapted from 13).

ing to the standards, this alarm must be triggered after 15 seconds of continuous pressure (23). As the last safety mechanism, the device itself reduces the pressure by automatically relieving the breathing system. At that time, the device alerts us with a medium level alarm (blue colour) and a "pressure relief" display. Unlike the previous alarm, this one takes twice as long before it goes off, i.e. it is triggered after 30 seconds. The duration of relief depends on the preset flow of fresh gases. With a flow rate between 14 l/min and 18 l/min, the relief lasts 30 seconds, then it is interrupted and the pressure slowly increases again for 30 seconds. This is followed by reopening of the valve. The system is relieved in 30 seconds. With lower flow rates (below 14 l/min), the relief duration was shorter, i.e. 1–3 seconds. This quantitative experiment was carried out with multiple repetitions in the Simulation Centre of the Medical Faculty of Maribor. Dräger Primus anaesthesia workstation and METI HPS simulator were used.

The higher the flows of fresh gases are set, the higher the pressure in the breathing system is achieved when the pressure relief valve is closed. Flows exceeding 8 l/min can create a high dangerous pressure in 20–30 seconds (16).

5. Reservoir bag and mechanical ventilation

In the traditional circle anesthesia breathing system, during mechanical ventilation, the reservoir bag is isolated with a special selector switch (Figure 1). In such a positioning of the components, we note a discrepancy between the set breathing volume and the actual one that occurs due to the ventilator-fresh gas coupling. Fresh respiratory gases from the inflow of fresh gases are pooled with gases from the mechanical ventilator. Example: at a set tidal volume of 500 ml, a respiratory rate of 10 min^{-1} and the inspiration/expiration rate I:E = 1 : 2, inspiration lasts 2 seconds. If the flow of fresh gases is 6 l/min (100 ml/second), the desired tidal volume (500 ml) is enhanced by additional 200 ml on inspiration. Thus, a pooled volume of 700 ml is delivered to the patient (200 ml more than we set on the ventilator). In most modern anaesthetic ventilators, the volume delivered to the patient is independent of the flow of fresh gases. There are three approaches to solving this problem:

- fresh gas decoupling;
- fresh gas compensation;
- fresh gas interruption (17).

Hereinafter, we will limit our discussion to fresh gas decoupling, which is schematically shown in Figure 6. This mode of ventilation is the only one among the mentioned three approaches that influences the reservoir bag during

mechanical ventilation. Figure 6 shows the flows of respiratory gases during inspiration, when the decoupling valve of fresh gases is closed. Gases from the ventilator are directed into the inspiratory limb to the patient. Due to the closed decoupling valve, the flow of fresh gases, instead of being added to the flow from the ventialtor, is directed into the reservoir bag through the absorber. Thus, the reservoir bag functions as a collector of fresh gases, similarly as in manual mode of ventilation. During the expiration phase, the engine in the electric ventilator moves the piston upwards and pulls into the cylinder fresh gases together with gases from the reservoir bag and the expiratory arm of the breathing system.

And where can problems arise? Two scenarios are possible. In the first, the reservoir bag that is damaged or punctured, so that gases leak out of it, can unexpectedly detach from the system. The inflow of fresh gases that fills the reservoir bag escapes into the surroundings during inspiration and thus contaminates the operating theatre with anaesthetics. During expiration, the ventilator draws air from the operating theatre through the damaged reservoir bag. The respiratory gases are diluted because they are mixed with the air from the atmosphere. The patient thus receives a lower fraction of oxygen on inspiration (FIO2) and a lower proportion of inhaled anesthetic. In 2004, Sandberg and Kaiser (18) described a case that occurred in a Dräger Fabius GS anaesthesia workstation (19), where an operation was already underway when the patient was found to be allergic to latex, and therefore the latex reservoir bag was replaced with a latex-free one. The replacement bag had a hole, but the leakage through it could not be detected, because the device cannot perform checking during mechanical ventilation. A few minutes after the replacement it was found that the reservoir bag was empty, and the concentration of oxygen, nitrogen oxide and inspiration anaesthetic had decreased. The error in the reservoir bag was detected when they switched from mechanical ventilation to manual ventilation. During expiration, the surrounding air entered into the reservoir bag and diluted the respiratory gases, so the proportions of O_2, N_2O and anaesthetics decreased accordingly. But despite the hole in the reservoir bag, the alarm on the device was not triggered. Therefore, we must pay attention to the values obtained from the monitoring of respiratory gases.

A similar case was described by Kuruma et al. in 2013, where problems due to the change of CO_2 absorber occurred during surgery (20). Recent versions of absorbers, such as Dräger CLIC, allow it to be replaced during operation of the appliance. In this case, the inflow of fresh gases was set at 4 l/min, and the concentration of sevoflurane to 1.5 %. When the absorber was replaced, the proportion of oxygen in the inhaled air decreased from $F_IO_2 = 38\,\%$ to 34 %, the proportion of sevoflurane decreased from 1.4 % to 1.1 %, and the bispectral index (BIS) increased, which indicated a lower depth of anaesthesia. In the operating theatre, the staff noted an anaesthetics smell. This case also shows that attention should be paid to the reservoir bag during mechanical ventilation.

The second potential scenario deals with a case whee the reservoir bag is under-filled. In such a case, problem occurs during expiration when the ventilator tries to pull the gases out of the empty reservoir bag. This scenario was simulated at the Simulation Centre using Dräger Primus anaesthesia workstation and a METI HPS-simulator (CAE Healthcare, Sarasota, Florida), where

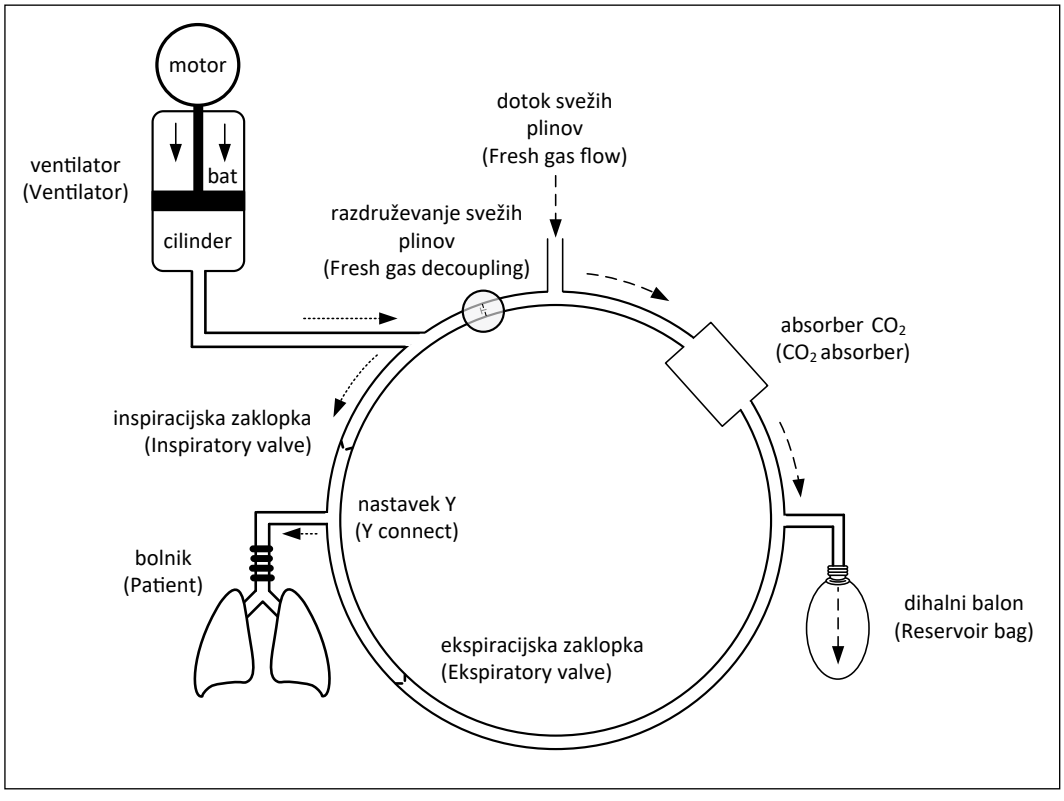

Figure 6: Fresh gas decoupling during inspiration.

the flow of fresh gases was adjusted to the lowest possible value of 200 ml/min of air in manual mode of spontaneous breathing (42 ml/min of oxygen). The simulator had oxygen consumption set to 250 ml/min, while the delivery was six-fold lower (below metabolic flow). Due to greater oxygen consumption than delivery, the partial pressure of oxygen in the reservoir bag was decreasing and consequently the reservoir bag shrank. The appliance emitted an alarm of low fresh gases flow (FG LOW OR LEAK) and low proportion of oxygen in inhaled breath (INSP O2 LOW). When the simulator tried to pull gases from the empty reservoir bag at inspiration, it caused negative pressure and triggered an alarm (PRESSURE NEGATIVE). In this alarm, the manufacturer recommends increasing the flow of fresh gases and, if necessary, using the Oxygen flush. The negative pressure occurred as a result of the simulator's spontaneous breathing. Negative pressure would also be obtained with spontaneous breathing, in the event that the tube to which the reservoir bag is connected is either folded or obstructed. In the case of mechanical ventilation, only the alarm (FGLOW OR LEAK) would be detected, as the piston of the electric ventilator would stop when pulling gasses from the reservoir bag and thus would not create a negative pressure (this applies to the Dräger Primus anaesthesia workstation).

In 2015, Vinay et al. described a case when using the Dräger Primus anaesthesia workstation (21), the position of the head and neck of a nine-year old child was changed during surgery, and as a result, the tracheal tube moved. Due to this movement, the tracheal tube cuff was no longer functioning and the respiratory gases started to leak. The respiratory volume (V_T) decreased from 280 ml to 200 ml. An alarm (LOW FRESH GAS FLOW) was triggered. The patient was

maintained on mechanical ventilation with a low flow of fresh gas set at 1 l/min. On the onset of alarm, the proportions of oxygen, nitrogen oxide and inspiration anaesthetics did not change. They detected an error in the tracheal tube cuff and re-inflated it. They also found that the reservoir bag was emptied. Oxygen flush activation followed, and due to mixing of respiratory gases with 100 % oxygen, the fraction of inspired oxygen (FIO_2) increased from 40 % to 69 %. At the same time, the proportion of isoflurane decreased from 1.0 % to 0.7 %. A decrease in the proportion of nitrous oxide was noted too. In the discussion, the authors summarise the incorrect conclusions that due to the empty reservoir bag during expiration the ventilator creates a negative pressure that opens the valve on the ventilator itself and allows the entry of external air from the operating theatre. Therefore they expected that after mixing with air the gases would be diluted, which however did not happen. The anaesthetic ventilator on the Dräger Primus system does not have a valve that would open if a negative pressure was generated (the authors apparently believed that it had). On expiration, the electric piston does not move to the values that would create a negative pressure.

The protection against negative pressure on the Dräger Fabius GS devices is slightly different (NEGATIVE PRESSURE RELIEF); there the valve opens when the negative pressure reaches a value between -7.5 and -9 cm H_2O. Then air is released from atmosphere into the ventilator cylinder, which dilutes the respiratory gases (22).

Fresh gas decoupling is possible only when using a ventilator with an electric drive (piston and cylinder) or a descendant ventilator (hanging bellows). In both cases, it is possible to achieve a negative pressure that pulls gases from the reservoir bag. In an ascendant ventilator (standing bellows) fresh gas decoupling is not feasible because expiration ends with a positive pressure (5,22).

Extreme caution is required when using high oxygen flush during mechanical ventilation. Oxygen flush activation (35–75 l/min) during inspiration can cause barotrauma when using anaesthesia workstation that do not have a built-in fresh gas decoupling system. In fresh gas decoupling systems, the high flow during inspiration is directed to the reservoir bag and not to the patient. In this case, oxygen flush can also be used during inspiration (23).

Fresh gas decoupling systems are integrated in the following anaesthesia workstations: Dräger Fabius GS, Dräger Narkomed 6000, Dräger Narkomed 6400, Dräger Primus, Dräger Apollo, Dräger Zeus and Datascope Anestar (22,24).

A fresh gas compensation system for solving the problem of discrepancy between the set tidal volume and the actual one is used in the following anaesthesia workstations: GE Datex-Ohmeda Aestiva/5, GE Datex-Ohmeda ADU Carestation, GE Aisys CS^2, GE Avance CS^2, and GE Aespire 7100/7900 SmartVent. These systems carry out continuous measurement of volume and flows of respiratory gases during inspiration and expiration, and continuously adjust the volume generated by the ventilator (22). In these systems, the reservoir bag has no function in controlled mechanical ventilation.

The third option for solving the problem of discrepancy in the respiratory volumes is fresh gas interruption (17). This method is used in the Dräger Julijan anaesthesia workstation (25). In this case too, the reservoir bag has no active role in controlled mechanical ventilation.

6. Conclusion

When using modern anaesthetic workstations, we have to know to some extent their function in order to ensure the patient's safety. Modern systems have built-in new technologies that ensure accurate respiratory volumes, however, there are differences between traditional systems. It should be pointed out that in fresh gas decoupling systems the reservoir bag is an active component of the breathing system during mechanical ventilation and it functions as a respiratory gas collector unit. It is important to monitor it, particularly in the case that NEGATIVE PRESSURE or FRESH GAS LOW alarms are triggered. The reservoir bag also has a monitoring function in mechanical ventilation.

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