South Afr J Anaesth Analg. 2023;29(5 Suppl 1):S49-53
https://doi.org/10.36303/SAJAA.3027

South Afr J Anaesth Analg
ISSN 2220-1181 EISSN 2220-1173

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Anaesthetic workstation

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Keywords: anaesthetic workstation, gas supply, breathing circuit, ventilators

Introduction

Anaesthesia aims to provide an environment where the surgeon has the best possible surgical conditions and the patient remains comfortable, safe, and pain-free.

The anaesthetic machine is the central component that facilitates monitoring of physiological functions, precisely delivering oxygen and volatile anaesthetic to the patient and eliminating carbon dioxide and excess gas from the system. A ventilator provides support in cases where the patient cannot maintain adequate minute ventilation through spontaneous breathing.

The functional anatomy of the anaesthetic delivery system

Gas supply[1-4]

The anaesthetic machine has a dual gas supply. The primary source of oxygen, medical air, and nitrous oxide is through the central pipeline system. For safety reasons, there must always be a backup source of oxygen. The backup source is provided by oxygen cylinders mounted at the back of the anaesthetic workstation. The gas supply system is divided into three sections depending on the pressure of the gases in each section (see Figure 1: Gas supply to the anaesthetic workstation).

High-pressure system[1,2,4,5]

The oxygen E-cylinder supplies oxygen at a very high pressure. A full E-cylinder has a gauge pressure of around 137 bar (or 2 000 psig) and an oxygen volume of 660 litres. The pressure decreases as the E-cylinder is depleted and can be used to determine how much oxygen is still available in the cylinder. A high-pressure reduction valve is located between the cylinder and the machine, so the pressure reaching the intermediate pressure system is around three bar or 45 psig.

The pin index safety system (PISS) is a safety feature that ensures the correct line connection to the correct cylinder. Each type of gas cylinder head has holes arranged in a specific configuration. Each gas's yoke assembly has metal pins arranged in the same mirror configuration as on the cylinder head. The metal pins must fit into the corresponding holes to create an effective seal. This prevents the accidental connection of the wrong pipe to the wrong gas cylinder.

Intermediate pressure system[1, 2, 4]

This part of the circuit starts after the high-pressure regulator from the cylinders and includes all the pipes from the pipelines and ends with the secondary pressure regulators.

Pipeline gases are delivered at an intermediate four-bar pressure (55 psig). The pressure difference between oxygen from the pipeline and the pressure of three bar in the cylinder line means that oxygen will preferentially come from the pipeline unless its pressure drops below the three bars in the cylinder line. Secondary pressure regulators are present in the lines to reduce the pressure further before the gas reaches the flowmeters.

Safety mechanisms are in place to prevent the delivery of a hypoxic mix to the patient. The first level of protection is the diameter index safety system (DISS). Every piped gas terminates in a specific size and shape connection and is colour-coded. The pipes that carry the gases to the machine are also colour-coded, and they have specific size and shape connectors corresponding to those on the pendant.

An oxygen supply sensor is part of the intermediate pressure system before the secondary pressure regulators. The alarm is triggered when there is a decrease in the pressure within the oxygen line, indicating an oxygen supply failure. Notably, the sensor is present in the pipe where pipeline oxygen and oxygen from the cylinder have already been combined. If the oxygen cylinder is left open, the oxygen failure alarm will not alert the anaesthetist about low pipeline pressure but will only sound once the oxygen in the cylinder is depleted. It is thus essential to close the cylinder when pipeline oxygen is used.

When the oxygen supply dwindles, a valve in the system will reduce or terminate the flow of other gases in the system. This valve is sometimes called a "fail-safe" valve. Since the pressure in the system influences this valve, it may lose its protective function if another gas pressurises the oxygen line.

The oxygen flush bypasses the vaporiser and can deliver 100% oxygen between 35 and 75 litres per minute. It is used to flush

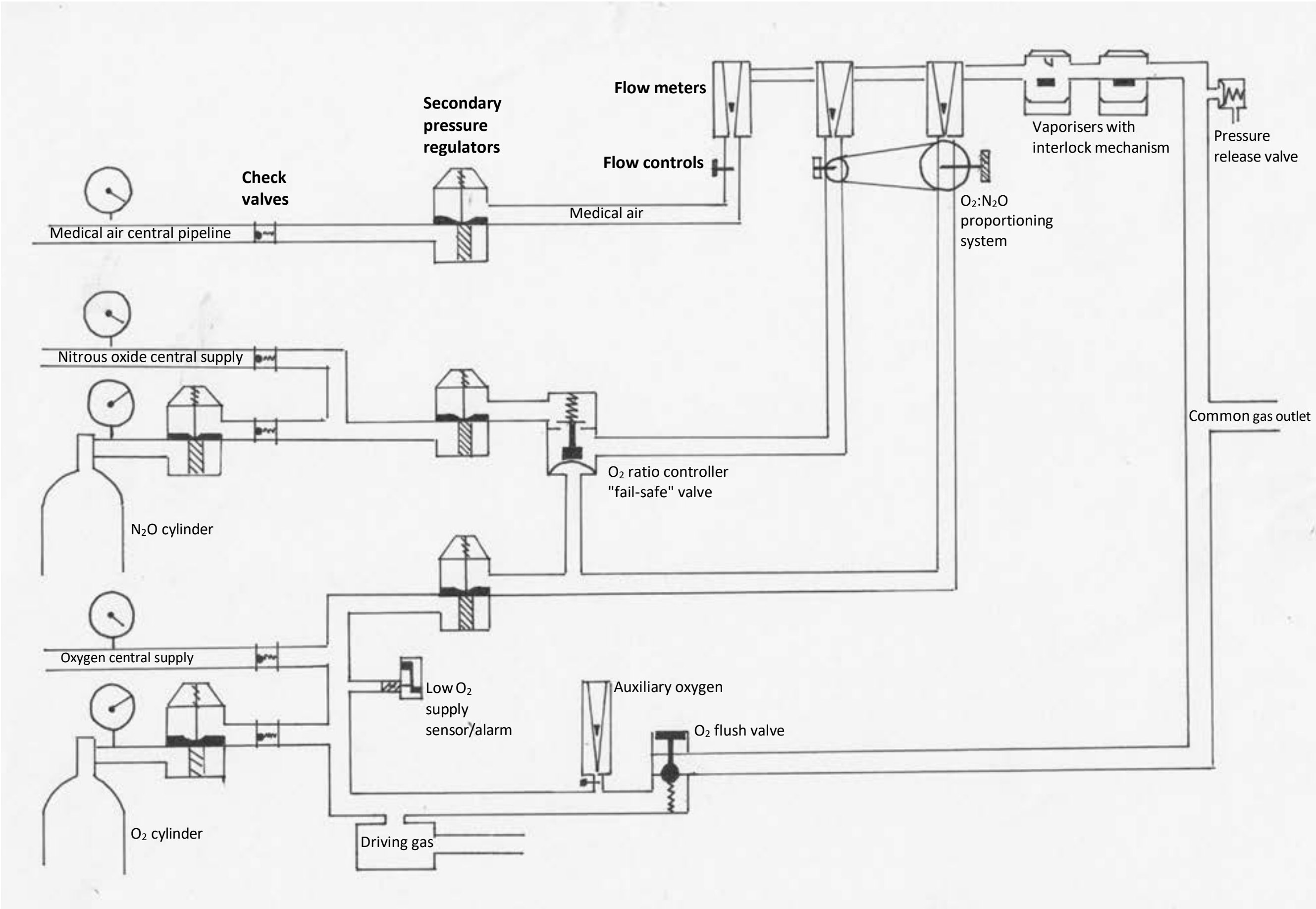

Figure 1: Gas supply to the anaesthetic workstation

the system in case of a leak or to rapidly increase the oxygen concentration in the system. The high flow rate can cause barotrauma if the oxygen flush is used during the inspiratory phase. A decoupling mechanism can negate this risk.

Some machines have an auxiliary oxygen flow meter on the oxygen line that bypasses the vaporiser. This oxygen port can provide oxygen even when the machine is not switched on.

Low-pressure system

The low-pressure system starts at the secondary pressure reduction valves and extends to the fresh gas outlet. The different gases join a common manifold that leads to the vaporisers. The anaesthetist determines the composition and volume of the final gases reaching the fresh gas outlet through the differential selection of the flow rates for the various gases, as well as the proportion of the gas that passes through the vaporiser.

Gases enter the low-pressure system and pass through an oxygen-nitrous oxide proportioning system. This device can be mechanical, electronic, or pneumatic. In mechanical devices, a chain connects the oxygen and nitrous oxide control knobs so that an increase in nitrous oxide will increase oxygen, and a decrease in oxygen will result in a decrease in nitrous oxide. Electronic devices use a paramagnetic analyser to continuously monitor the concentration of gases and to electronically regulate the flow of nitrous oxide relative to oxygen. A pneumatic device works on the balance of the O_2 and N_2O pressure. There is a resistor in both the oxygen and the nitrous pipelines. The resistor in each line causes back-pressure on a diaphragm. A connector shaft separates the oxygen and nitrous diaphragms. The connector shaft controls a "slave valve" in the nitrous line. If the O_2 pressure drops, the back-pressure on the O_2 diaphragm reduces, and a valve moves into the N_2O orifice to reduce or halt the flow.

The flow meters can be physically tapered glass tubes or displayed electronically. Each glass flowmeter must be calibrated for its specific gas, as the flow of each gas depends on density and viscosity. A float is present within each flowmeter. Its diameter is slightly smaller than the narrowest part of the tube. The space between the tube and the float is known as the annular space. As flow increases, it exerts an upward pressure on the float. A gravitational force on the float counteracts the upward pressure. The float will hover at the level where the two forces are in equilibrium. The top of the float indicates the flow rate on a calibrated scale in the tube. At low flows, the flow around the float is laminar and dependent on the viscosity of the gas. At higher flows, the flow around the float becomes turbulent, and its behaviour depends on the gas density.

The outlets of the different flowmeters lead to a common manifold that carries gas towards the vaporiser. The flowmeters join this manifold sequentially. Traditionally, the flowmeters have been very fragile and the glass of the tubes could break. Should this go undetected, the gases that join the manifold proximally can escape through the broken glass, decreasing its flow in the distal part of the manifold. The concentration of the last gas to be added will then be higher than what is set. Since all the hypoxic safeguards are proximal to this point, this situation can go undetected unless the oxygen analyser picks up the problem at the patient's end. To make the common gas mixture safer, oxygen should be the last gas added to the common gas flow so that its concentration will be the highest.

Electronic devices continuously measure the gas content, concentration, and flow and digitally display the parameters. The machine then uses microprocessors to make the necessary changes.

Common gas flow

The common gas flow then flows through the anaesthetic vaporiser, where it picks up the vapour of the anaesthetic agent. Vaporisers will not be discussed in this article.

Breathing circuit

The fresh gas flow (FGF) enters the breathing circuit after passing through the vaporisers. Note that the breathing circuit also has an internal component that is not visible to the anaesthetist. Essential prerequisites of the breathing circuit are that it must have a low-resistance conduit with a reservoir that matches the patient's minute volume and a conduit to vent waste gas. The most used circuit in anaesthesia is the circle system.

Gas flow in a pipe is influenced by various factors that can be explained by Hagen-Poiseuille's and Ohm's laws.[6]

Ohm's law: $R = {}^{\Delta P}/_{Q}$

Hagen-Poiseuille's law: $\Delta P = {}^{LvV}/_{r^4}$

Regarding Ohm's law, the flow (Q) is directly proportional to the pressure gradient and inversely proportional to resistance. By using Hagen-Poiseuille's law, the pressure difference can be determined. The pressure gradient is directly proportional to the viscosity of the gas (v), the length of the tube (L), and the flow rate (V), and inversely related to the radius (r) to the power of four.

The airway resistance is affected by the type and the rate of the flow. Flow can be laminar, turbulent, or a combination. For laminar flow, Hagen-Poiseuille's law can be used. Therefore, flow moves down the pressure gradient. The flow in the centre of the pipe is faster than the flow rate at the outer core. At high flow rates, laminar flow can also become turbulent.

In contrast, when the flow is turbulent, the particles move randomly in all directions. Turbulent flow occurs at high flow rates or constrictions in the tube. The flow rate is the same throughout the stream. Due to this, the pressure gradient within the pipe increases to maintain forward flow, and resistance also increases. Resistance is directly related to the flow rate squared. To reduce resistance, the length of the circuit should be minimised, the diameter maximised, and any constrictions that can result in turbulent flow must be avoided.

In the case of the circle system, the internal part of the breathing circuit includes the ventilator, the CO_2 absorber canister, the adjustable pressure limiting (APL) valve, and unidirectional valves and sensors to monitor flow, oxygen concentration, and pressure within the breathing circuit.

The CO_2 absorber is critically important in the circle system as the exhaled gas from the patient remains part of the system. The CO_2 must be removed from the system to prevent rebreathing of the CO_2 and diluting the FGF. The reaction in the CO_2 absorber depends on the chemical composition of the absorbent (see Table I).

Soda lime can absorb 26 litres of CO_2 per 100 g of soda lime. The capacity is influenced by the surface area of the absorbent in contact with CO_2, the specific capacity of the different absorbent materials, and the amount of non-saturated absorbent remaining. Smaller particles have a larger surface area compared to larger particles, but it increases the resistance to gases flowing through the canister. The capacity of the absorbent to remove CO_2 may be reduced to 10–20 litres due to various factors not discussed in this article.

A colour change warns the anaesthetist that the absorbent is reaching its capacity. Ethyl violet is added to the absorbent. Adding CO_2 to the absorbent gradually lowers the pH in the canister. Ethyl violet is a colourless substance that changes to violet if the pH decreases below 10.3.[3]

The APL valve is an operator-managed valve that allows gas from the breathing circuit to be vented to the scavenger system. In the fully open position, the patient can breathe spontaneously. When the valve is partially closed, it provides continuous positive airway pressure (CPAP) in the spontaneously breathing patient. When the valve is closed further, it will generate enough positive pressure to allow the anaesthetist to manually provide positive pressure ventilation to the patient.

Table I: Chemical reactions of the CO_2 absorption system[1, 7]

CO_2 reaction with soda lime Net reaction: $CO_2 + Ca(OH)_2 = H_2O + heat$	
Sequential reactions with NaOH as the catalyst: $CO_{2\ (gas)} + H_2O_{\ (liquid)} \rightleftarrows H_2CO_{3\ (aqueous)}$ $H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2H_2O + heat$ $Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH + heat$	Sequential reactions with KOH as the catalyst: $CO_{2\ (gas)} + H_2O_{\ (liquid)} \rightleftarrows H_2CO_{3\ (aqueous)}$ $H_2CO_3 + KOH \rightarrow K_2CO_3 + 2H_2O + heat$ $K_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + KOH + heat$
CO_2 reaction with lithium hydroxide monohydrate $2LiOH + H_2O + CO_2 + heat \rightarrow Li_2CO_3 + 3H_2O$	

Unidirectional inspiratory and expiratory valves are present in the circuit to prevent the backflow of gases within the system. These valves must not get stuck. An expiratory valve stuck in the closed position will cause barotrauma as the expired gases have nowhere to go. An expiratory valve stuck in the open position will result in the inappropriate rebreathing of CO_2.

A reservoir bag forms part of the circuit. The size of the bag is relative to the minute volume required by the patient. A two-litre bag is used for adults, a one-litre bag is available for children, and a 500-millilitre bag is used for babies. As the reservoir bag is the most compliant component of the circle system, it could serve as a protective mechanism against excessive pressure in the system. In combination with the APL valve, it provides a means of manually ventilating the patient. Given its position in the expiratory limb of the circle system, it usually fills with exhaled gases and excess FGF.

An oxygen sensor is placed within the inspiratory limb or Y-piece. This is the last safety check to prevent a hypoxic mixture from being delivered to the patient. The oxygen sensor can be a galvanic fuel cell or a paramagnetic sensor. The latter is used more commonly in newer anaesthetic machines.

Ventilators [1-3, 8]

Ventilators have come a long way since the "iron lung" ventilators used during the polio pandemic. Ventilators today have sophisticated ventilation modes to enable mechanical ventilation to be as physiological as possible. The ventilators on anaesthetic machines generally do not have all the advanced modes available on intensive care ventilators.

Ventilators are classified according to the type of design into bellow-, piston-, and turbine-driven, or according to their power source as pneumatic, electric, or a combination of the two. The position of the ventilator in the circuit depends on the type of ventilator.

Bellows ventilators

Bellows ventilators have a double-circuit system . This means that the driving gas and the fresh gas never mix unless there is a leak in the bellows. A transparent dome covers the bellows, allowing the anaesthetist to observe the movement of the bellows and confirm ventilation visually.

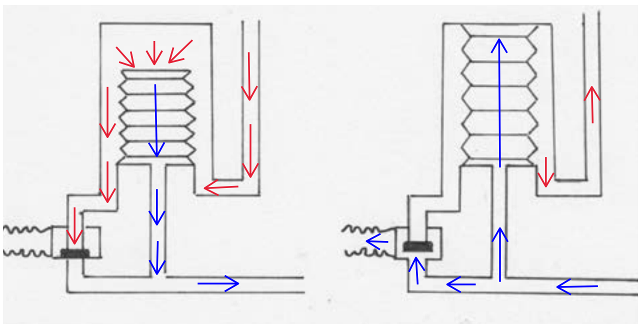

Figure 2: Ascending bellows ventilator

The bellows are filled with the gas components of the FGF, including the volatile agents if those are used. During inspiration, a valve opens that forces the driving gas (usually O_2 or a mixture of O_2 and medical air) into the transparent casing surrounding the bellows. The positive pressure created inside the dome pushes the bellows downwards and displaces the fresh gas in the bellows into the inspiratory limb of the breathing circuit.

The passive recoil of the patient's chest wall during exhalation moves the expired gases into the expiratory limb of the circuit. The return of gases to the ventilator pushes the bellows upwards, and the driving gas that previously filled the dome escapes into the atmosphere. The driving gas does not contain volatile anaesthetics, so the pollution of the operating theatre is not a concern.

The volume of driving gas needed per minute equals the minute volume. Oxygen will be drawn from the cylinder in the event of pipeline failure. The amount of oxygen needed includes both the volume of the driving gas and the volume needed for ventilation of the patient. The volume consumed in the breathing system equals the FGF per minute times the F_iO_2. In this regard, the bellows ventilator will consume oxygen much faster than a piston ventilator and will affect the calculation of the time available before the oxygen cylinder is depleted.

Bellows ventilators are pneumatically driven, but electricity is needed to control the valves that regulate the pneumatic process. The respiratory cycle time and tidal volume are electronically regulated.

Bellows ventilators have a volume sensor in the circuit that detects a change between the set tidal volume and the delivered tidal volume. These sensors provide feedback to the microprocessor to change the volume of the driving gas to offset the change. It takes a few breaths before the set and delivered tidal volumes are similar.

If there is a leak in the breathing system, the ascending bellows will fail to reach the top of the dome after expiration. This safety feature is not available in descending bellows as the weight of the bellows will allow them to reach the bottom even when there is a leak. A leak can thus easily go undetected.

The disadvantages of the bellows ventilator:

- It uses a lot of oxygen to drive the ventilator, this is an undesirable feature in areas where oxygen supplies are limited.
- Presence of auto-positive end-expiratory pressure (auto-PEEP) due to the weight of the bellows.
- A perforation in the bellows can result in barotrauma as the pressurised driving gas will enter the bellows, mix with the fresh gas, and the entire volume will be forced into the lungs; it also dilutes the fresh gas and risks patient awareness or emergence.
- The tidal volume may be inaccurate under certain conditions.
- Fresh gas compensation is needed to avoid excessive tidal volumes at high flows.

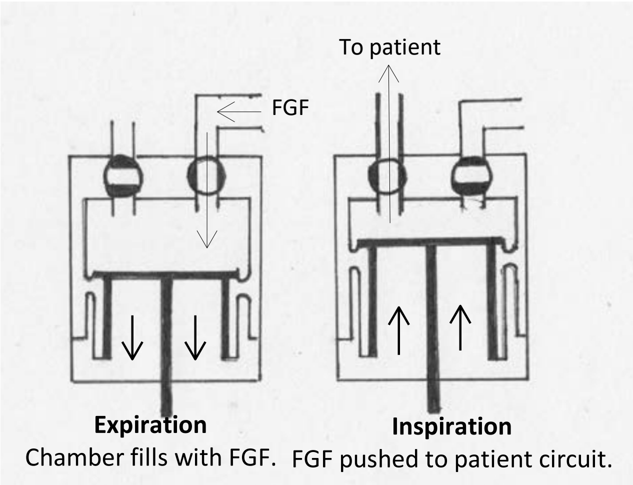

Figure 3: Piston ventilator

Piston ventilators

A piston ventilator is placed within the anaesthetic machine proximal to the unidirectional inspiratory valve. It consists of a cylinder lined with a soft, flexible plastic insert. The piston drive is inside the cylinder. The piston moves backwards and forwards in the cylinder and can be compared to the plunger in a syringe. The distance it moves to deliver the tidal volume is electronically determined, as is the timing of the cycles. A gear system drives the piston forwards and backwards. Backward movement allows the cylinder to fill, while forward movement moves the gas volume into the patient circuit.

The benefits of piston ventilators:

- There is no need for a driving gas to drive the ventilator, making it the preferred ventilator in areas where oxygen is in short supply. In the event of pipeline failure, a lesser volume of oxygen will be drawn from the oxygen cylinder. The calculation of time remaining before the oxygen is depleted is thus only dependent on the FGF.
- More precise delivery of tidal volume.
- More precise control over airway pressure management due to the presence of pressure sensors.
- Oxygen (or medical air) is not vented into the atmosphere, making it more economical.
- Volutrauma is avoided through the fresh gas decoupling mechanism.
- No auto-PEEP.
- Quiet.
- Single circuit system.

The disadvantages of piston ventilators:

- Leaks cannot be visually detected, detection only relies on low-pressure alarms.
- A leak can lead to hypoventilation.
- There is a chance that room air can be entrained when the piston returns to the starting position.

Other types of ventilators include the volume reflector ventilator and the turbine ventilator, which are more commonly used in intensive care ventilators.

The delivered tidal volume on older ventilators was influenced by the FGF. The delivered tidal volume was the sum of the set tidal volume and the FGF. With increased FGF, the anaesthetist had to manually decrease the set tidal volume to avoid volutrauma. Modern machines can keep the tidal volume close to what the anaesthetist sets. The two mechanisms through which this is achieved are fresh gas compensation and fresh gas decoupling.

The mechanism found in the piston and descending bellows ventilators is called fresh gas decoupling. A more accurate name may have been "fresh gas diversion". On inspiration, a valve between the FGF and the ventilator closes, diverting the FGF to the reservoir bag. This prevents the FGF from being added to the tidal volume during inspiration. Gas is drawn from both the reservoir bag and the FGF for the next breath. There is a risk that room air can be entrained into the system if the reservoir bag is not correctly assembled or is absent and the FGF is inadequate.

Ventilators must have alarms to warn about deviations in the system. These alarms include a low and high peak inspiratory pressure alarm, low expired volume alarm, low end-tidal carbon dioxide, and low oxygen supply.

Conclusion

The anaesthetist needs to be familiar with the components of the anaesthetic workstation. Daily tests are essential and knowledge of the system will help find the source of a problem, such as a leak, a circuit pressure problem, etc. It ensures that the workstation works optimally and can deliver a safe anaesthetic to the patient.

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