The anaesthetic machine

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Abstract

Modern anaesthetic machines have improved greatly since 1917 when Boyle modified the American Gwathmey apparatus of 1912 to develop the ubiquitous continuous flow anaesthetic machine. Despite this, the basic principles and many components remain, albeit in modernized form. Gas is still supplied to the machine from a high-pressure source which is stepped down to a safe pressure supplying the breathing system. Flowmeters control gas flow and allow for adjustment of different inspired concentrations of gases. A vaporizer adds anaesthetic vapour to the inspired gas which is then delivered to the patient via a dedicated breathing system. But modern improvements in safety, requirements for increased monitoring and improved technology have driven change in the anaesthetic machine. Modern anaesthetic workstations employ digital technology to deliver safe and measured anaesthesia to patients. Despite improvements in safety and reliability, routine checking of anaesthetic machines before use is essential. The Association of Anaesthetists of Great Britain and Ireland (AAGBI) have developed a standardized checklist for users to ensure all components of the anaesthetic machine are functioning appropriately.

Keywords Adjustable pressure limiting valve; anaesthetic machine; Bodock seal; hypoxic guard; non-interchangeable screw thread; rotameter; scavenging

Royal College of Anaesthetists CPD Matrix: 1A03

Learning objectives

After reading this article, you should be able to:

- describe the basic functions of an anaesthetic machine
- outline common safety measures integrated into an anaesthetic machine
- describe the pre-anaesthetic check of an anaesthetic machine according to AAGBI 2012 guidelines

Introduction

Modern anaesthetic machines perform a range of complicated and precise functions, facilitating the administration of safe anaesthesia to patients. Knowledge of how individual anaesthetic machines work is not expected as there are many variations of machine in common use. The Association of Anaesthetists of Great Britain and Ireland (AAGBI) developed a standardized checklist[1,2] for checking anaesthetic machines and a laminated copy of the checklist should be attached to every anaesthetic machine to assist the anaesthetist checking the machine. In addition, the machine check is a topic often examined as part of the Royal College of Anaesthetists Primary FRCA examination. In this article, we will use the checklist as a structure to explore the functions and safety features built into anaesthetic machines in the UK.

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Check self-inflating bag available

The simplest anaesthetic machine is an anaesthetist! With a self-inflating bag, it is possible to ventilate and oxygenate an apnoeic patient. A self-inflating bag must be available as a back-up when using any anaesthetic machine in case of catastrophic machine failure.

Perform manufacturer's (automatic) machine check

Even though anaesthetic machines need to be manually checked before use, modern machines are able to perform self-checks. These check internal systems that may not be easily accessible and identify problems with the machine. All machine checks are documented to ensure a record of safe practice.

Power supply

Modern anaesthetic machines work primarily with mains electricity and must be plugged in to use. They should be plugged into the hospital's essential mains supply, which has an automatic generator backup to prevent power loss in an emergency. Anaesthetic machines also usually have an emergency battery to power the machine if mains supply fails.

Gas supplies and suction

Gas is supplied to the anaesthetic machine either from the main wall hospital pipeline supply or from cylinders. If the oxygen supply fails an audible and visual alarm sounds, indicating there is no oxygen delivery to the patient. The alarm is powered by the oxygen supply pressure and activates when oxygen pressure falls below 2 bar. Once activated, room air will be used for ventilation until the oxygen supply returns.

Gas and vacuum pipelines – 'tug test'

Medical gases are moved around hospitals via the piped medical gases and vacuum (PMVG) systems, sometimes informally called the 'pipeline.' These supply oxygen, nitrous oxide and air at a pressure of 4 bar to specialized outlets called Schrader valves (Figure 1). Schrader valves are individually colour coded and have collars unique to each gas to prevent accidental misconnection. Each Schrader valve connects to a colour coded flexible hose delivering the specific gas to the anaesthetic machine. If the connection is faulty, or the wrong hose is connected to the wall Schrader valve, the hose will disconnect from the wall when pulled during the 'tug test'. The machine end of the colour-coded hose has a screw connection specific to each gas called a

Figure 1 Schrader valves.

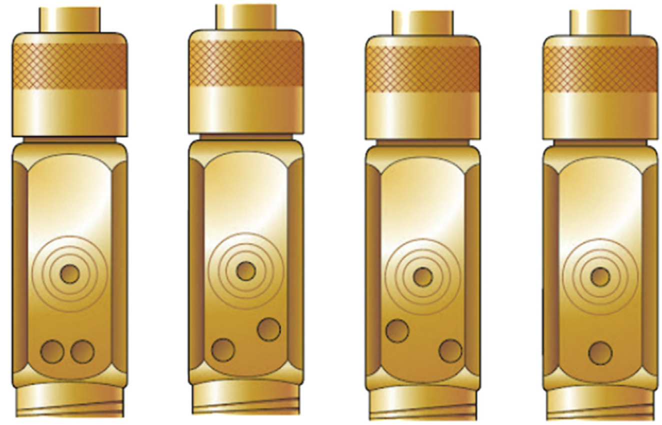

Figure 3 Pin-index system. Note the different configuration for each gas.

non-interchangeable screw thread (NIST) to further reduce the risk of wrong gas administration (Figure 2). The NIST will only screw onto the anaesthetic machine at the gas specific receiver it was designed for.

Cylinders filled and turned off

In case of PMVG failure, anaesthetic machines have a backup oxygen supply. This is usually an E sized cylinder containing 680 litres of oxygen stored at 137 bar. Pins project from the machine cylinder yoke in a specific geometric pattern that aligns with holes on the oxygen cylinder valve. This is called the pin index system and ensures that only cylinders containing the correct gas can be attached to the machine (Figure 3). Different gasses have different pin indexes so only an oxygen cylinder can be connected to the oxygen cylinder yoke of a machine. A neoprene washer surrounded by a metal ring called a Bodock (BOnded DisK) seal[3] keeps the cylinder-machine seal airtight. A pressure regulating valve prevents high cylinder pressure reaching the machine by dropping gas pressure to 4 bar.

Flowmeters working (if applicable)

Individual gases move through the anaesthetic machine via a system called the back bar, before being mixed and delivered to the patient via the common gas outlet (CGO). In order to deliver a safe anaesthetic, accurate measurement of individual gas flows is essential. While modern anaesthetic machines have electronic flow measurement, the Rotameter™ is the most common non-digital anaesthetic flowmeter (Figure 4). Rotameters are variable-orifice, fixed-pressure devices. They consist of a needle valve that alters the flow of gas into the rotameter tube. A rotating bobbin or ball is housed within a tapered anti-static glass transparent tube that is wider at the top than the bottom. The bobbin will rise as gas flows increase and stop where gravity equals the pressure of upwards gas flow.

Figure 2 Non-interchangeable screw thread connections.

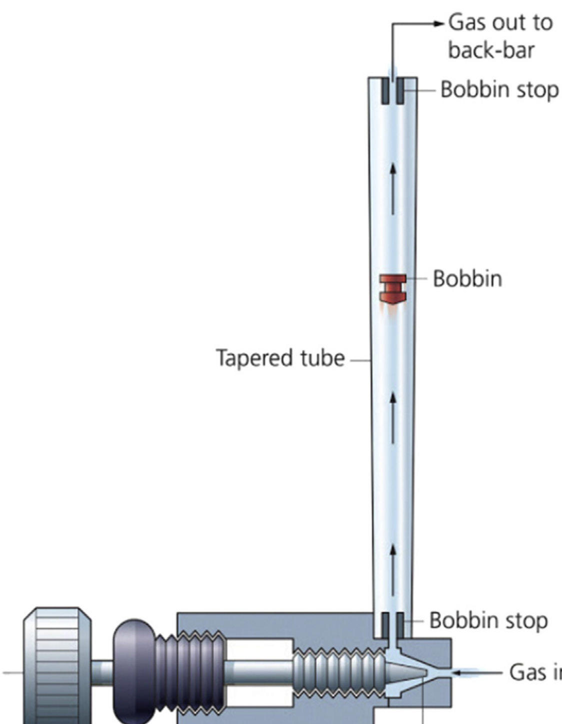

Figure 4 A flow control (needle) valve and flow meter.

At low flow rates, the bobbin spins at the bottom of the tube. Here, the length of the bobbin is larger than the space between the bobbin and the tube wall. This creates a tube and gas flow becomes laminar and dependent on viscosity (as determined by the Hagan-Poiseuille Law). At high flows, due to the taper making the distance between the tube and the bobbin bigger, the bobbin length is less than the space between it and the tube wall creating an orifice. As such, gas flow is turbulent and governed by gas density (as predicted by Reynolds number). As each gas will have different viscosity and density, rotameters are specifically calibrated for one gas at 20°C and 1 bar pressure. Calibration is accurate to 2%.

In the UK, rotameters have standardized safety features to prevent accidental incorrect gas administration. Oxygen rotameters are always on the left of the rotameter block with an octagonal knob that protrudes more than others and is colour-coded white (nitrous oxide is blue, air black). The rotameter bobbin spins showing that it is free-floating, and an anti-static coating is applied to the rotameter tube that prevents the bobbin sticking to the wall and giving a false reading. Rotameter flow scales also glow in the dark for easy identification in low light conditions. Oxygen is the last gas added to the fresh gas mixture so it is not accidentally lost if other rotameters are damaged as this would cause a lower concentration of oxygen to be delivered than desired. Leaving the flowmeters, oxygen passes through the vaporizer and on to the CGO.

Hypoxic guard working

To prevent hypoxic gas mixes, oxygen and nitrous oxide are linked via a hypoxic mixture prevention device that either mechanically, pneumatically or electronically links the two flowmeters. This ensures the delivered oxygen concentration never inadvertently falls below 25%.

Mechanical devices link the oxygen and nitrous oxide rotameter valves with a chain and have a stop fitted to the oxygen rotameter valve that ensures oxygen gas flow never falls below 175–250 ml min^{-1}, even when turned off. Pneumatic devices rely on a ratio mixer valve with oxygen and nitrous oxide exerting pressure either side of a diaphragm. As nitrous oxide flow and therefore pressure increases, the change in pressure also causes the oxygen flow to increase. Electronic devices use a paramagnetic analyser to continuously analyse the fresh gas flow delivered to the patient. If inspired oxygen concentration falls below 25%, nitrous oxide flow is stopped until the oxygen concentration increases again.

Oxygen flush working

An emergency oxygen flush is supplied upstream from the back bar and flow meters. It is therefore at high pressure (4 bar) and does not pass through the vaporizer. It supplies oxygen to the common gas outlet at 35–75 L min^{-1}. It must be used with care as it will dilute anaesthetic vapour in a breathing system and can cause volutrauma or barotrauma.

Suction clean and working

A suction device able to produce −400 mmHg suction at 40 L min^{-1} flow should be available. This may be attached to the anaesthetic machine or be a separate unit.

Breathing system

Whole system patent and leak free using the ‘two-bag’ test

There are many places from which gas may leak from an anaesthetic machine. Whilst this may be not noticed at high gas flows, at low gas flows even a small leak can have a large effect.

Standardized connections are used to connect breathing circuits to the CGO. The CGO has a 22 mm male and a 15 mm female connection and provides an airtight seal for gas leaving the anaesthetic machine and flowing into the breathing circuit to the patient. Unidirectional valves and pressure relief valves downstream to the vaporizer ensure the flow of gas through the anaesthetic machine goes in the correct direction. Without these, back pressure could damage the anaesthetic machine, the vaporizer or cause harm to the patient. These unidirectional valves are usually visible, enabling them to be checked and stuck valves identified with greater ease.

A ‘two-bag’ test, described in the AAGBI checklist, checks whether the unidirectional valves move appropriately and also tests the adjustable pressure-limiting (APL) valve. The APL valve is a spring-loaded pressure relief valve used to adjust the peak gas pressure delivered to the patient when they are being ventilated manually or breathing spontaneously. It can be screwed fully down to only release pressures of greater than 60 cm H_2O, or unscrewed to open at a pressure less than 1 cm H_2O. It is designed to reduces the risk of patient harm and facilitate ventilation. Anaesthetic machines also have an intrinsic pressure relief valve between the vaporizer and CGO that prevents damage to the machine.

In order to prevent leakage of gas, vaporizers are connected to the back bar with secure male-female connections sealed with neoprene O-Rings.

Vaporizers – fitted correctly, filled, leak free, plugged in (if necessary)

Most anaesthetic machines have the capacity to hold one or two vaporizers to help deliver quantified levels of anaesthetic vapour to a patient. These attach to the back bar, downstream from the flowmeters. Modern vaporizers have specific interlocking safety features to prevent two vaporizers being used simultaneously. Vaporizers are colour-coded for their volatile anaesthetic agent and have a unique key filling system that can only be used with the agent they are calibrated for. Visible liquid fill-level gauges and a non-spill reservoir that allows tilt of up to 180° further increase their safety. The topic of vaporizers is covered more extensively elsewhere in this journal series with the variations in their design and use expanded more fully.

Soda lime – colour checked

Modern anaesthetic machines usually use a circle breathing system to increase efficiency. Circle systems reduce the amount of volatile anaesthetic agent and gases used by recycling exhaled gas and agent back to the patient. In order to prevent toxic build-up of carbon dioxide, a canister of soda lime is built into the anaesthetic machine to remove, or ‘scrub’, the carbon dioxide from the exhaled gas before it is mixed with additional fresh gas and returned to the patient. The chemical reaction that removes carbon dioxide generates heat and water, so the gases that leave the soda lime are warm and moist which helps to reduce intraoperative heat loss. As the reaction happens, a pH change occurs in the soda lime causing a dye in the soda lime to change colour. This allows users to see when the soda lime needs to be replaced as its capacity to absorb carbon dioxide has been exhausted.

Alternative systems (Bain, T-piece) – checked

Although most modern anaesthetic machines have a circle breathing system built into them, many also have an auxiliary common gas outlet (ACGO) onto which a different breathing circuit can be attached in an emergency, or when specific breathing circuits are required such as in paediatrics. If present, the anaesthetic machine will have a selector switch to direct gas to either the CGO or ACGO.

Correct gas outlet selected

The CGO or ACGO will have 15 mm female, 22 mm male universal connectors. Selecting the correct gas outlet is essential to ensuring patient safety.

There may also be a smaller auxiliary oxygen flowmeter mounted to the side of the anaesthetic machine for administering oxygen to the patient, for example during sedation cases. This flowmeter receives oxygen separately from the back bar flowmeters and common gas outlet and may closely resemble the oxygen flowmeters commonly found on the walls of hospital wards.

Ventilator

Working and configured correctly

Many modern anaesthetic machines have integrated ventilators that are digitally controlled and pneumatically powered. These commonly permit ventilation to a set pressure (pressure mode) or to a set volume (volume mode), allowing variations in inspiratory and expiratory times and pressures to be individually set by the user. Modern anaesthetic machine ventilators are highly sophisticated and resemble those used in critical care environments. Many ventilators are able to perform self-testing to ensure that they are safe to use. It is beyond the scope of this article to explore the intricacies of ventilators and ventilation modes further.

Scavenging

Working and configured correctly

International law now stipulates maximum environmental levels for anaesthetic gases in the workplace (Table 1). To avoid breaching these, waste gases are removed from the breathing circuit via a low pressure, high volume scavenging system consisting of four components.

The collecting system connects to the patient breathing circuit or ventilator via a 30 mm conical connection. Collecting systems have an 'air brake' to prevent pressure damage to the patient's lungs. The air brake is a large bore opening, such as slits in the collecting system casing, that allows room air to enter the system if excess negative pressure develops or scavenged gas to exit the system if positive pressure develops in the scavenging. Waste gases then travel through wide bore tubing, known as the transfer system, to a reservoir referred to as the receiving system. Alongside the reservoir, the receiving system also has a flow indicator, filter and valves to prevent excessive negative pressure (triggered at -0.5 cmH_2O) or positive pressure (triggered at $+5$ cmH_2O).

Gas is discarded via disposal systems. In the UK these are usually active systems, reliant on a powered fan and high flow, generating low pressure and moving 75 L min^{-1} gas continuously or 130 L min^{-1} at peak flow. Other systems such as vacuum scavenging (low flow, high pressure) and passive venturi/ejector scavenging are used in other countries around the world.

Maximum environmental levels for anaesthetic gases in the workplace

Gas	Maximum concentration (parts per million)
Nitrous oxide	100
Enflurane	50
Isoflurane	50
Halothane	10

Table 1

Monitors

Working and configured correctly; alarm limits and volumes set

The AAGBI stipulate in their minimum monitoring standards that inspired and expired oxygen, carbon dioxide, nitrous oxide and volatile anaesthetic concentrations and airway pressure be monitored throughout an anaesthetic.[4] Many modern anaesthetic machines incorporate monitoring of these and other physiological parameters. Machines also have pre-set alarm limits for parameters as well, generating audible and visual alarms when exceeded.

Airway equipment

Full range required, working, with spares

An anaesthetic machine is useless without means of supporting a patient's airway. Through safely checking the anaesthetic machine and ensuring that airway and emergency airway equipment is available, users are able to provide anaesthesia to patients in a safer way.

Conclusion

Despite containing many complicated electrical components, by exploring how modern anaesthetic machines work from first principles as we have in this article, it is possible to establish an understanding of the safety features and functionality common to all anaesthetic machines.

The AAGBI machine checklist, used before every theatre list in the UK, provides a systematic approach to understanding the anaesthetic machine and discussing its function. This will prove useful when troubleshooting problems that may occur everyday practice, or when explaining its function in high stress environments such as examinations. ◆

REFERENCES

1 Association of Anaesthetists of Great Britain and Ireland. Checking anaesthetic equipment 2012. *Anaesthesia* 2012; **67:** 660–8.

2 Association of Anaesthetists of Great Britain and Ireland. Checklist for anaesthetic equipment 2012. *Anaesthesia* 2012; **66:** 662–3, http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2044.2012.07163.x/abstract.

3 Sinclair C, Thasad M, Barker I. Modern anaesthetic machines. *Cont Educ Anaesth Crit Care Pain* 2006; **6:** 75–8.

4 Association of Anaesthetists of Great Britain and Ireland. Recommendations for standards of monitoring during anaesthesia and recovery 2015. *Anaesthesia* 2016; **71:** 85–93.