Modern anaesthetic machines

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Anaesthetic machines dispense a mixture of gases and vapours in varying proportions to control a patient’s level of consciousness, analgesia, or both during surgical procedures. The machine performs four essential functions: (i) provides oxygen; (ii) accurately mixes anaesthetic gases and vapours; (iii) enables patient ventilation; and (iv) minimizes anaesthesia-related risks to patients and staff.

History

Coxeters built HEG Boyle’s original machine in 1917 under the direction of Lord George Wellesley (great-grandson of the first Duke of Wellington).1 It was a modification of the American Gwathmey apparatus of 1912 and became the best-known early continuous flow anaesthetic machine. The British Army used a portable version during the First World War. The early Boyle’s machine had five elements which are still present in all modern machines.

(i) A high-pressure supply of gases. It housed two oxygen and two nitrous oxide cylinders in a wooden box.
(ii) Pressure gauges on oxygen cylinders and fine-adjustment reducing valves. These produce a manageable breathing system pressure. It had a spirit flame to warm these and prevent obstruction of gas flow from ice.
(iii) Flowmeters to control gas flow rate and adjust proportions of gas delivered.
(iv) A metal and glass vaporizer bottle for ether.
(v) A breathing system comprising a Cattlin bag, three-way stopcock and facemask.

Modifications (e.g. dry bobbin flowmeters in 1933, pin-index system in 1952) were driven by a consideration for greater safety.

The modern anaesthetic machine

Anaesthetic machines have six basic subsystems:

(i) gas supplies: pipelines and cylinders;
(ii) gas flow measurement and control (flowmeters); (iii) vaporizers; (iv) gas delivery: breathing system and ventilator; (v) scavenging; (vi) monitoring.

Box shaped sections of welded steel or aluminium provide a rigid metal framework mounted on wheels with antistatic tyres and brakes. Antistatic measures improve flowmeter performance and, where flammable vapours are used, reduce the risk of ignition.

Companies offer modifications of the standard machine to suit different environments. Compact or wall-rail mounted designs may be suitable for areas where space is restricted. These may have a single position back bar e.g. Pneupac 110 (Pneupac Limited), Frontline Genius Compact Anaesthesia Machine (Blease). Larger models may be trolley or ceiling-mounted (pendant) e.g. Aestiva IS-Pendant Version (Datex-Ohmeda). MRI-compatible models e.g. Prima SP Anaesthetic Machine (Penlon), are made from non-ferrous metals and can be used safely up to the 1000 Gauss line.

Workstations have been developed for total i.v. anaesthesia. In these, syringe drivers are located on a ‘back bar’ or mounted onto tube and rail systems (e.g. Datex-Ohmeda, B Braun fm anaesthesia) with integrated monitoring.

A typical modern workstation has open architecture with easily cleaned work-surfaces, and drawers, shelves and rails to accommodate customized accessories. Machines are mains powered and a rechargeable battery provides up to 60 min of backup.

Gas supplies

Piped gas supply

Piped oxygen is drawn from a central oxygen source, which may be a vacuum insulated evaporator, a cylinder manifold or an oxygen concentrator. Piped medical air may be supplied from either a cylinder manifold or a compressor with an outlet filter (to achieve adequate purity). Nitrous oxide is supplied from a cylinder manifold.

Key points

Modern anaesthetic machines retain the essential elements of the original Boyle’s concept.
Safety specifications have ensured standardization of features between different makes of machine.
Anaesthetic hazards attributable to machine faults may be reduced by pre-use checks and regular maintenance.
Anaesthetists should be familiar with the safety features of anaesthetic machines that prevent harm to patients and staff.
Computer-controlled anaesthesia systems are becoming more common.
Gases are fed into a labelled and colour-coded pipeline distribution network, which terminates in self-closing (Schrader) sockets at the wall. Flexible pipelines connect the terminal outlet to the anaesthetic machine. Reducing valves ensure the pipeline pressure of anaesthetic gas services is 4 bar. Flexible pipelines have three components:

(i) *Schrader probe*. To prevent misconnection to the wrong gas service, the probe for each gas supply has a protruding indexing collar with a unique diameter, which only fits the Schrader socket assembly for the same gas.

(ii) *Flexible hosepipe*. Originally the hoses were made of black reinforced rubber with short lengths of coloured sheaths at each end. Modern hoses are colour-coded for each gas (oxygen is white; nitrous oxide, French blue; medical air hose, black/white).

(iii) *Non-Interchangeable Screw Thread (NIST) connection to the anaesthetic machine*. This ensures a hose connection specific to each gas service. It comprises a nut and probe. The probe has a unique profile for each gas, which fits only the union on the machine for that gas. The nut has the same diameter and thread for all gas services, but can only be attached to the machine when the probe is engaged. The term NIST is in fact misleading; the screw thread does not determine the unique fit. A one-way valve ensures unidirectional flow.

**Cylinders**

Cylinders usually serve as a backup, should the central gas supply fail. They are mounted on yokes attached to the machine. A valve block screws into the open end of the cylinder. It is marked with the gas chemical symbol, tare weight, pressure at the last hydraulic test and a serial number. Turning a longitudinal spindle, set within a gland screwed into the block, opens the valve. Leaks are prevented by the compression of a nylon ring around the cylinder neck (UK). This melts at relatively low temperatures to allow gas to escape in case of fire and minimize the risk of explosion.

Additional safety features of cylinders include:

(i) *Molybdenum steel alloy construction*. This is stronger and lighter than its carbon steel predecessor.

(ii) *Colour-coding* for each gas or vapour.

(iii) *Pin-index system*. This prevents the accidental connection of a cylinder to the wrong machine yoke. The cylinder valve block bears an arrangement of holes, into which fit pins protruding from the yoke.

(iv) *Bodok seals* (bonded disk). These are non-combustible neoprene washers with aluminium edges, interposed between the cylinder head and yoke to provide a gas-tight seal.

The pressure in a full oxygen or air cylinder at 20°C is 137 bar. The pressures in full nitrous oxide and carbon dioxide cylinders are approximately 52 and 58 bar, respectively. Each gas entering the machine from a cylinder flows through a filter, one-way check valve and primary regulator. Bourdon gauges are fitted adjacent to each yoke and pipeline connection. These are calibrated, labelled and colour-coded for each gas service.

**Pressure regulators**

Modern machines have several primary and secondary regulators. Primary regulators reduce potentially dangerous high cylinder pressures to the machine working pressure of 4 bar (420 kPa). Some manufacturers adjust the cylinder regulators to just under 420 kPa, which allows the machine to preferentially use pipeline gas. Some regulators weep their cylinder contents, hence the importance of turning a cylinder off after a machine check. Secondary regulators level out gas delivery. Machine working pressures may vary by up to 20%, for example during periods of peak hospital demand. Pressure fluctuations can cause parallel changes in (and damage to) flowmeter performance. Secondary regulators set below the anticipated decrease in pressure will make the emergent pressure more uniform.

In order to minimize connections and potential leaks, the NIST connection, cylinder yoke, primary regulator and pressure gauges are housed in a single cast brass block.

**Gas flow measurement and control**

Flow control valves govern the transition from the high to the low-pressure system. These reduce the pressure from 4 bar to just above atmospheric as gas enters the flowmeter block. Flow rate is indicated by a flowmeter. Conventional flowmeters (rotameters) consist of a needle valve, valve seat and a conically tapered and calibrated gas sight tube containing a bobbin. Flowmeters may be mechanical or electronic.

In a mechanical system, gas entering the sight tube lifts the bobbin in proportion to flow. The bobbin floats and rotates without touching the sides, giving an accurate indication of gas flow. Flow is read from the top of the bobbin. Features reducing inaccuracy to within 2% include:

(i) Sight tubes for each gas are individually calibrated at 20°C and 101.3 kPa; they are non-interchangeable.

(ii) Tubes have different lengths and diameters, and may have a pin-index system at each end.

(iii) Tubes are leak-proof because of neoprene washers (O-rings) at both ends of the flowmeter block.

(iv) The tubes have an antistatic coating on their inner and outer surfaces. This prevents the bobbin from sticking to the tube wall.

(v) The bobbin is visible throughout the length of the tube and has vanes to improve its rotation in the gas flow.

Modern oxygen flowmeters are arranged to feed downstream of other gases in the event of a proximal leak. The oxygen control knob is larger, more protruding and differently shaped compared with those of air or nitrous oxide. In the UK, the oxygen control is positioned at the extreme left of the flowmeter bank. However,
in other countries, it may be positioned at the extreme right of the bank.

Some modern units may use microprocessors to control gas flow; flow is indicated electronically by a numerical display or ‘virtual flow tubes’ (e.g. Drager Fabius GS; Datex-Ohmeda S/15 Anaesthesia Delivery Unit). These allow easy identification of gas flows in a darkened theatre and the export of electronic data to an information system. In the event of an electrical failure, there is a pneumatic backup, which continues the delivery of fresh gas. Other units may have an illuminated flowmeter bank. Some have the ability for ultra-low flow anaesthesia at rates of <1 litre min⁻¹. Auxiliary oxygen flowmeters are featured on larger units; they are separate from the back bar flowmeters and common gas outlet.

**Hypoxic mixture prevention devices**

Modern machines have interlocked oxygen and nitrous oxide flow controls. This prevents inadvertent delivery of a hypoxic inspired gas mixture, as the ratio of oxygen to nitrous oxide concentrations never decreases below 0.25. This can be achieved by a mechanical, pneumatic or electronic mechanism.

Mechanical devices (e.g. Ohmeda) use a chain to link flow control valves for oxygen and nitrous oxide. This system may fail to account for other gases, such as air, reducing the oxygen concentration to <25%. A stop fitted to the oxygen flowmeter control valve ensures a minimum flow of oxygen at 175–250 ml min⁻¹, even with the valve apparently closed.

Pneumatic devices (e.g. MIE) use a ratio mixer valve. Oxygen supplied to this valve exerts a pressure on one side of the diaphragm, which is opposed by the pressure of nitrous oxide on the opposite side. The diaphragm construction ensures an increase in oxygen flow rate by a ratio of 25% of any increase in the nitrous oxide flow rate.

Electronic devices (e.g. Penlon) use a paramagnetic oxygen analyser to continuously sample the gas mixtures from the flowmeters. If inspired oxygen fraction decreases below 0.25, the nitrous oxide is temporarily cut off; whereas an increase in inspired oxygen fraction will temporarily restore nitrous oxide flow.

**Vaporizers**

Vaporizers sit on the back bar of the anaesthetic machine, downstream of the flowmeter block. Manifolds for vaporizers are commonly of the Selectatec type (Ohmeda) or similar Interlock type (Drager). Each Selectatec station on the back bar has two male valve-ports, with O-rings for a gas-tight fit, which seat the vaporizer’s two female ports. Some units use a ‘back entry’ vaporizer mounting. Modern vaporizers (e.g. Datex-Ohmeda Tec 5, 6 and 7) have several safety advantages over their predecessors: (i) an interlock to isolate vaporizers not in use; (ii) a clear indication of liquid level; (iii) a non-spill reservoir with up to 180° of allowable tilt; (iv) a keyed-filler or pour-fill systems prevent filling with an incorrect volatile agent and minimize leaks; and (v) an increased wick capacity.

Continuous flow machines use variable bypass vaporizers, which may be mechanically or electronically controlled. Each is designed and calibrated for a specific anaesthetic vapour. The heated blended vaporizer was designed for desflurane. Recent innovations have included injection of volatile agent into the fresh gas stream, at a rate calculated (by computer) to produce the desired concentration. Datex-Ohmeda has replaced conventional vaporizers with Aladin vaporizer cassettes in their S/15 Anaesthesia Delivery Unit. The cassettes are more lightweight (2–3 kg), are virtually service-free and have no restrictions for tilting. Integrated electronic fresh gas flow measurement of varying gas mixtures enables the unit to dispense more accurately a dialled concentration, compared with traditional vaporizers.

Safety features on, or downstream of the back bar include:

(i) **Oxygen failure warning device.** British Standard BS4272 specifies that this alarm should be powered solely by the oxygen supply pressure in machine piping and activated when that pressure decreases below 200 kPa. In case of complete oxygen failure, ventilation with room air is facilitated.

(ii) **Spring-loaded non-return valve.** This prevents surges in back pressure from damaging vaporizers and flowmeters.

(iii) **Pressure relief valve.** This is set at 30–40 kPa to prevent back pressure from damaging vaporizers and flowmeters.

(iv) **Emergency oxygen flush,** which is supplied from the high-pressure circuit upstream of the flowmeters and back bar, and provides flow between 35 and 75 litre min⁻¹.

All gas mixtures (from back bar or oxygen flush) exit the machine through a 22 mm male OD/15 mm female ID conically tapered outlet. BS4272 specifies an anti-disconnect device. A fuel cell oxygen analyser should be attached here. In addition, modern machines have mini Schrader gas sockets for air and oxygen. These may be used to power Venturi systems for a bronchoscope or Sanders injector.

**Gas delivery—breathing systems and ventilators**

A full discussion of these is beyond the scope of this review.

**Breathing systems**

Either circle systems or T piece configurations are used. In modern workstations, circle systems come readily assembled and are, in all but the most compact versions, integrated into the unit. A single housing comprises the carbon dioxide absorber, adjustable pressure limiting (APL) valve, reservoir bag, circuit pressure gauge and switch to select manual or mechanical ventilation mode. A switch may allow the absorber to be removed from the circle. The Anmedic Q-Mix (Anmedic) circle system uses a shunt valve to adjust the proportion of exhaled gas that passes through the absorber canister. In this way, end-tidal carbon dioxide concentration may be manipulated. Some systems use a circulating pump or fans, in place of unidirectional valves, to reduce resistance to gas flow. Modern breathing systems strive to have...
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a minimal number of connections in order to reduce the potential for leaks. Parts in contact with patient gas are autoclavable (except the fuel cell oxygen analyser) and latex-free.

Adjustable pressure limiting valve
APL valves are used in both types of breathing circuit. It allows excess gas to escape when a preset pressure is exceeded, thus minimizing the risk of barotrauma to the patient. Many APL valves do not have calibrations and are adjusted empirically to give a desired peak inspired pressure. Breathing circuits include a pressure gauge for monitoring circuit pressure to assist with setting the APL valve. Modern valves, even when screwed down fully, open at a pressure of 60 cm H2O. Newer machines may have an electronically adjustable and calibrated APL valve. Most valves are encased in a hood for gas scavenging.

Ventilators
Ventilators may be integrated with the anaesthetic machine or configured later. These are often electronically controlled and pneumatically powered. The autoclavable bellows are often suitable for adult and paediatric use. Traditionally, anaesthetic machine ventilators have had a minimal number of controls. The anaesthetist could vary minute volume by setting tidal volume and ventilatory frequency directly or by adjusting inspiratory time, inspiratory flow rate and the ratio of inspiratory to expiratory time. The newest models resemble critical care ventilators in their capabilities. These may perform self-test upon start-up (using dual processor technology), volume or pressure controlled ventilation modes, assisted spontaneous ventilation and electronically adjustable PEEP. Sophisticated spirometry compensates for changes in fresh gas flow, small leaks or patient compliance. They are marketed as being suitable for a broader range of patients from neonates receiving 20 ml tidal volumes to patients with ARDS.

Scavenging
Modern scavenging has four components for collecting, transferring, receiving and disposal of waste gases from the breathing circuit:

(i) The collecting system comprises a gas-tight shroud enclosing the APL valve of the breathing circuit (or expiratory port of the ventilator) utilizing 30 mm conical connections. Some systems (Ohmeda AGS) have an over-pressure relief valve which blows at 1 kPa.
(ii) The transfer system comprises wide bore tubing leading from the collecting systems to the receiving system.
(iii) The receiving system comprises a reservoir, air brake, flow indicator and filter. A closed system requires a dumping valve to prevent excessive negative pressure developing (0.5 cm water at 30 litre min⁻¹ gas flow) and a pressure relief valve to prevent excessive positive pressure (5 cm H2O at 30 litre min⁻¹ gas flow).
(iv) Disposal systems are active and high flow in the UK. The sub-atmospheric pressure required is generated by an exhauster unit, which uses a fan to generate a low pressure, high volume system capable of removing 75 litre min⁻¹ at a peak flow of 130 litre min⁻¹. Other countries use active and low flow systems using a higher-pressure vacuum (USA) or passive Venturi/ejector systems (Scandinavia).

Monitoring
A full review of monitors is also beyond the scope of this article. Some anaesthetic machines conduct an automatic self-test on start-up, e.g. Primus (Drager). The test results are recorded and displayed. This is not intended to replace the pre-use check by an anaesthetist.

Anaesthesia units must incorporate certain minimum equipment-related monitors. North American standards specify airway pressure, volume of expired gas and inspired oxygen concentration. Monitors for other anaesthetic gas concentrations and physiological parameters may be incorporated into the machine.

Machines are configured with respect to their monitors in one of two ways. Modular systems require stand-alone physiological monitors to be added separately. Preconfigured systems are manufacturer-assembled, with an integrated display and prioritized alarms. These may have automated anaesthetic record keeping (AARK) for anaesthesia delivery and physiological parameters.

Conclusion
The evolution of the modern anaesthetic machine has been driven by safety standards. This has led to a marked consistency in the appearance and control features of marketed units in the UK. Anaesthetists can quickly learn to use these different machines because of such standardization. The current diversity in standards between different countries has prevented the international distribution of a single anaesthesia workstation. Even as computer-controlled systems have become more common, anaesthetists should be familiar with the basic concepts that underlie the subsystems of the modern anaesthetic machine. Problems have been reported with all parts of anaesthesia systems. Pre-use checklists, regular inspections and maintenance can help reduce hazards.

References

Please see multiple choice questions 24–26.