Review Article

The Basic Anaesthesia Machine

Address for correspondence:
Dr. CL Gurudatt,
Department of Anaesthesia,
Mysore Medical College and
Research Institute, Mysore,
Karnataka, India.
E-mail: dattguru55@gmail.com

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CL Gurudatt
Department of Anaesthesia, Mysore Medical College and Research Institute, Mysore, Karnataka, India

ABSTRACT

After WTG Morton's first public demonstration in 1846 of use of ether as an anaesthetic agent, for many years anaesthesiologists did not require a machine to deliver anaesthesia to the patients. After the introduction of oxygen and nitrous oxide in the form of compressed gases in cylinders, there was a necessity for mounting these cylinders on a metal frame. This stimulated many people to attempt to construct the anaesthesia machine. HEG Boyle in the year 1917 modified the Gwathmey's machine and this became popular as Boyle anaesthesia machine. Though a lot of changes have been made for the original Boyle machine still the basic structure remains the same. All the subsequent changes which have been brought are mainly to improve the safety of the patients. Knowing the details of the basic machine will make the trainee to understand the additional improvements. It is also important for every practicing anaesthesiologist to have a thorough knowledge of the basic anaesthesia machine for safe conduct of anaesthesia.

Key words: Anaesthesia machine, basic design, boyle machine, conventional flow meter, evolution and history, yoke assembly

INTRODUCTION

The most important piece of equipment that the anaesthesiologist uses is the anaesthesia machine. Safe use of anaesthesia machine depends upon an interaction between the basic design of the machine with its safety features and the knowledge and skills of the anaesthesiologist. The basic function of an anaesthesia machine is to prepare a gas mixture of precisely known, but variable composition. The gas mixture can then be delivered to a breathing system. Anaesthesia machine itself has evolved from a simple pneumatic device to a complex array of mechanical, electrical and computer – controlled components. Much of the driving force for these changes have been to improve patient safety and user convenience.[1] Though many modifications have been brought out still the basic design has not much changed. Hence, knowledge of the basic design of the anaesthesia machine is a must for all the practicing anaesthesiologists to understand the modern anaesthesia workstation.

HISTORY AND EVOLUTION

After anaesthesia was invented and introduced with the public demonstration of ether anaesthesia by WTG Morton in 1846, for many years an anaesthesia machine was not required for providing anaesthesia to the patients until oxygen (O_2) and nitrous oxide (N_2O) were introduced as compressed gases in cylinders by the late 19th century.[2] A metal skeleton was required for mounting these cylinders.

Boyle's machine was invented by Henry Edmund Gaskin Boyle in 1917. His machine was a modification of the American Gwathmey apparatus of 1912 and became the best known early continuous flow anaesthetic machine. The Boyles apparatus was first made by Coxeter and Sons, under the direction of Lord George Wellesly, which was later acquired by the British Oxygen Company (BOC). "Boyle" was the trade name of BOC. It was named so to respect the inventor, Boyle. However, Boyle was not the pioneer in manufacturing anaesthesia machines. Two other great men had done excellent work before him. One was James Taylor Gwathmey who was practicing in New York who invented the Gwathmey machine in 1912. Later, Geoffrey Marshal developed a machine during the First World War (1914-1918) based on the Gwathmey machine. Boyle, who developed his

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machine from Gwathmey's basic model in 1917, presented his invention at the Royal Society of Medicine in London in 1918. Even though Marshal had developed his machine much before Boyle, he presented his machine before the medical community in 1919, much later than Boyle. All the credit had gone to Boyle, although Gwathmey and Marshal had developed their machines before him.[3,4]

- 1921 – Waters to and fro absorption apparatus was introduced.[2]
- 1927 – Flow meter for carbon dioxide was included, the volatile controls were of the lever type and the familiar back bar made its first appearance.[2]
- 1930 – The plunger of the vaporiser appeared in the 1930 model.[2]
- 1930 – Circle absorption system was introduced by Brian Sword.[2]
- 1933 – Dry bobbin flow meters were introduced.[5]
- 1952 – Pin index safety system (PISS) by Woodbridge.[5]
- 1958 – Introduction of Bodok seal.[5]

FUNCTIONS OF ANAESTHESIA MACHINE

The machine performs four essential functions:

1. Provides O_2,
2. Accurately mixes anaesthetic gases and vapours,
3. Enables patient ventilation and
4. Minimises anaesthesia related risks to patients and staff.[6]

BASIC DESIGN OF A CONTINUOUS ANAESTHESIA MACHINE

The basic design of an anaesthesia machine consists of pressurised gases supplied by cylinders or pipelines to the anaesthetic machine, which controls the flow of gases before passing them through a vapouriser and delivering the resulting mixture to the patient through the breathing circuit [Figure 1].[7]

The early Boyle's machine had five elements, which are still present in modern machines: (1) A high pressure supply of gases, (2) pressure gauges on O_2 cylinders, with pressure reducing valves, (3) flow meters (4) metal and glass vapouriser bottle for ether and (5) a breathing system.[6]

The anaesthesia machine is a continuous flow machine in which all the components are mounted on a table. Box shaped sections of welded steel or aluminium provide a rigid metal framework mounted on wheels with antistatic tyres (Castors) and brakes. Antistatic measures improve flow meter performance and where flammable vapours are used, reduce the risk of ignition.[6]

Figure 1: Basic continuous flow anaesthesia machine with carbon dioxide absorber and closed circuit

The basic machine has provision for fixing two O_2 cylinders and two N_2O cylinders through the yoke assembly with PISS. There is also provision for connecting the pipeline gas source of O_2 and N_2O (from the wall outlet with quick couplers and yoke blocks at the machine end) instead of one of the cylinders at the yoke assembly. A pressure gauge is mounted on to the yoke assembly to read the pressure in the cylinder. Pressure regulators are located downstream of the yoke assembly, which reduce the high pressure in the cylinders to a low and constant pressure of 45-60 PSIG.[8] From the pressure regulators, there are connections through high pressure tubings constructed of heavy duty materials to the flow meter assembly, which is secured to the back bar of the machine by one or more bolts. The back bar supports the flow meter assembly and the vapourisers. At the end of the back bar, there is the common gas outlet to which the breathing circuits are connected to provide the anaesthetic vapour containing O_2 enriched gases to the patient.

The anaesthesia machine can be conveniently divided into three parts: (a) The high pressure system, which receives gases at cylinder pressure, reduces the pressure and makes it more constant, (b) the intermediate pressure system, which receives gases from the regulator or hospital pipeline and delivers them to the flow meters or O_2 flush valve and (c) the low pressure system, which takes gases from the flow meters to the machine outlet and also contains the vapourisers.[9]

THE HIGH PRESSURE SYSTEM

The high pressure system consists of all parts of the machine, which receive gas at cylinder pressure. These include the following: (a) The hanger yoke which connects a cylinder to the machine, (b) the yoke block, used to connect cylinders larger than size E or pipeline hoses to the machine through the yoke, (c) the cylinder pressure gauge, which indicates the gas pressure in the cylinder and (d) the pressure regulator, which converts a high variable gas pressure into a lower, more constant pressure, suitable for use in the machine.[9]

HANGER YOKE ASSEMBLY

The hanger yoke orients the cylinder, provides gas tight seal and ensures a unidirectional gas flow [Figure 2]. The workstation standard requirement is that there should be at least one yoke for O_2 and N_2O. If the machine is likely to be used in locations that do not have piped gases, it is advisable to have a double yoke, especially for O_2.[9]

The hanger yoke consists of: (1) The body, which is the principle framework and supporting structure, (2) the retaining screw, which tightens the cylinder in the yoke, (3) the nipple, through which gas enters the machine, (4) the index pins, which prevent attaching an incorrect cylinder, (5) the Bodok seal, the washer which helps to form a seal between the cylinder and the yoke, (6) a filter, to remove particulate matter and (7) the check valve assembly which ensures a unidirectional flow of gas through the yoke [Figure 2].[10]

PIN INDEX SAFETY SYSTEM

Machines are usually equipped with one or two E type cylinders that hang on specific hanger yokes. The medical gas pin-index safety system ensures that the correct medical gas cylinder is hung in the correct yoke. The system consists of two pins that are fixed in the yoke, and which fit into two corresponding holes in the cylinder valve. The two pins are in a unique configuration for each gas and should never be removed from the hanger yoke. Specific pin configurations exist for each of the medical gases supplied in small cylinders in order to prevent erroneous misconnections of gas supplies. A cylinder should never be force-fitted to a hanger yoke.[11] For O_2 the pin index number is 2-5 and for N_2O it is 3-5. Substitution of an E type N_2O cylinder for O_2 can occur if pins in the index face are missing or broken or if several washers are used simultaneously. This fault is deceptive because the PISS is thought fool proof. This defect can only be detected by direct inspection of the yoke and cylinder gas identity markings each time a cylinder is replaced on the machine.[12]

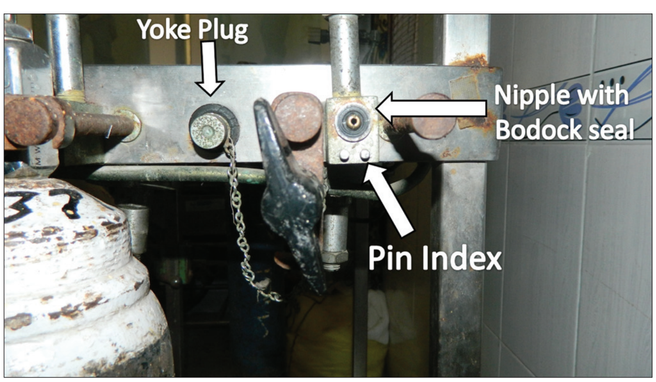

Figure 2: Yoke assembly with bodok seal and yoke plug

The check valve assembly prevents transfilling of empty cylinders. Since there is always a chance of check valves not functioning properly, yoke should not be left vacant and a yoke plug (which is a solid metal piece with a conical depression on one side and a hollow area on the other side for retention screw and nipple of the yoke respectively) should be fitted. Yoke plugs are usually kept chained to the machine [Figure 2].

BOURDON'S PRESSURE GAUGE

Cylinder pressure is usually measured by a Bourdon's pressure gauge, which is a flexible tube which straightens when exposed to gas pressure causing a gear mechanism to move a needle pointer.[13] In the older machines like in Boyle's mark-3, the front of the Bourdon's pressure gauge is covered by a heavy glass window and the back is covered by loosely fitted tin sheet. The idea being if there is a sudden increase in the pressure and the tube ruptures, then high pressured gases are vented from the back preventing injury to the patient and the anaesthesiologist. In machines like Boyle 'F', there were no pressure gauges for N_2O as it was thought that there is no use of the same as the pressure remains constant until all the liquid N_2O evaporates. In Boyle mark-3, pressure gauges were introduced for N_2O also so that once the indicator starts showing pressure less than 750 PSIG, the anaesthesiologist will come to know that all the liquid N_2O has evaporated and what remains is only N_2O gas. The pressure gauges are colour coded, white for O_2 and French blue for N_2O [Figure 3].

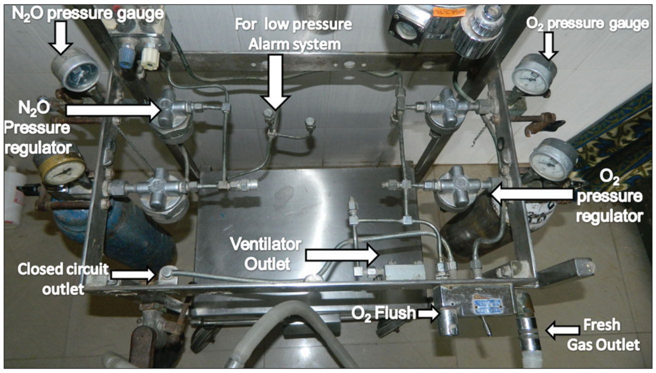

Figure 3: Internal assembly of basic anaesthesia machine when viewed from above with covering plate removed

YOKE BLOCK

It is a piece of metal, shaped like a cylinder valve that is pin indexed and has a port and a conical depression to fit into a yoke.[9] With the introduction of diameter index safety system for pipeline inlet connections, the use of yoke blocks have been discontinued in modern machines as they were associated with several hazards.

PRESSURE REGULATORS

These are the devices which reduce the high pressures in the cylinders to a lower and more constant pressure to maintain a constant flow [Figure 3]. The reasons for their presence are:

1. If there are no pressure regulators, then there will be a necessity for the anaesthesiologist to keep re-adjusting the flow control valves to maintain a constant flow as the cylinder pressure decreases with use, decreasing the flow.
2. The high pressure from the cylinders can produce damage to the flow control valves.
3. The high pressure can also produce barotrauma to the patient's lungs.
4. With lowered pressure supplied to the flow meters fine adjustments of the flow is possible.

The pressure regulators reduce the pressure of the O_2 cylinders from 2200 PSIG to 45-60 PSIG and the N_2O cylinders from 750 PSIG 45-60 PSIG.[9]

BASIC PHYSICS

The pressure regulators work on the basic principle "force = pressure × area". When force is kept constant with a spring and area inside the regulator is increased using a diaphragm, then automatically pressure of the gas decreases. By keeping the force exerted by the spring high, changes in the cylinder pressure due to use will not affect the reduced output pressure. The output pressure is fixed by the manufacturing company and hence these are called as 'fixed pressure regulators'.

MASTER AND SLAVE REGULATOR

With early anaesthesia machines (Boyle-F), if an O_2 cylinder becomes exhausted or the pipeline source failed, in the face of significant N_2O flow, the patient would receive a lower fraction of O_2 or even a hypoxic gas mixture. Especially before the advent of pulse oximetry, hypoxaemia and patient injury could occur unless the machine fault is immediately recognised by the anaesthesiologist.[14] In the subsequent anaesthesia machines (Boyle mark-3), since there was no separate O_2 fail safe mechanism, the N_2O pressure regulator was constructed in such a way that pressure of the O_2 flow was required to release the flow of N_2O. So, N_2O regulator was made to act like a 'slave' regulator to O_2 as the 'master' regulator. When this was introduced as a safety mechanism, it was thought that hypoxic mixture could not be delivered to the patient as O_2 in the pipeline supply or cylinder supply gets depleted, N_2O output from the N_2O regulator also would stop and anaesthesiologist will be alarmed as the reservoir bag collapses. This was not a fool proof system as still hypoxic mixtures could be delivered if the O_2 is cut off at the flow meters. Hence proportionating devices had to be introduced at the flow meter assembly in modern machines.

THE INTERMEDIATE PRESSURE SYSTEM

It includes the components of the machine which receive gases at reduced pressures usually 37-55 PSIG.[9] This in older machines includes the O_2 failure alarms, flow meter assembly and O_2 flush and in modern machines also include O_2 pressure fail safe systems, pipeline inlet connections, pipeline pressure gauges and ventilator power outlets.

O_2 FLUSH

There is a direct tubing connecting the O_2 pressure regulator to the O_2 flush. It gives 35-70 L/min of flow with a pressure of 45-60 PSIG [Figure 3]. Its main use is during the mask ventilation with a lot of leak between the mask and the patient's face especially in elderly patients and in patients with difficult airways and also acceptable power source for jet ventilation for providing partial, if not total, ventilatory support in most clinical situations.[15] When it is operated, even if the vapourisers are turned on, the patient will receive pure O_2 uncontaminated with N_2O and volatile agents. Inappropriate use of the O_2 flush valve has been associated with both barotrauma and intraoperative awareness. Barotrauma can occur because the flush valve allows fresh gas to enter the breathing circuit at a rate of approximately 1 L/s.[1] Also if it is accidently turned on and unobserved, patient may not be adequately anaesthetised. When the flush is activated, the flow meters may not show its activation but as it makes sufficient noise, the same can not be overlooked.[8]

THE FLOW METER ASSEMBLY

The flow meter assembly controls, measures and indicates the rate of flow of gas passing through it [Figure 4].[9] The flow meter assembly consists of flow control valve and flow meter sub-assembly.

Flow control valves

The flow control valve controls the rate of flow of a gas through its associated flow meter by manual adjustment of variable orifice. Flow control valve is also called as needle valve or pin valve. The valve mainly consists of the control knob, stem and seat. The control knob is colour coded and touch coded for each gas. The control knob is large, cylindrical in shape with wide flutes and coloured white for O_2 and is small, conical in shape with narrow flutes and coloured blue for N_2O. The machine standard requires a distance of 25 mm between the knobs.[9] The flow control knobs are turned counter-clockwise to open the gas flow in the flow meter and clockwise to close the gas flow.

The flow control knobs are connected to the stem which has a pin at its distal end. When the valve is closed, the pin fits into a seat of metal and no gas flows. When the stem is turned counter-clockwise, then an opening is created between the pin and the seat and gas starts

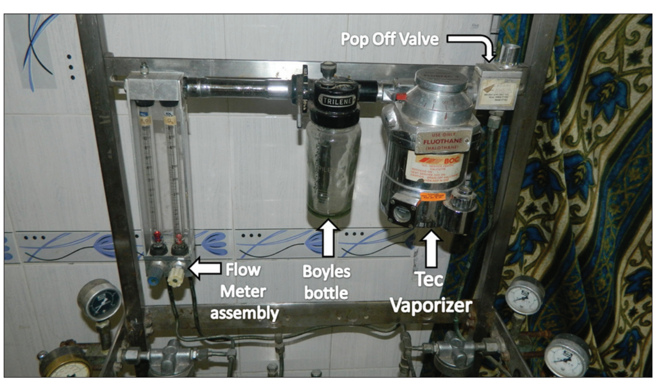

Figure 4: Flow metere assembly, back bar and pop-off valve

flowing into the flow meter. There are stops for the closed position and maximum opening position which prevent damage to the fine needle valve or disengage the stem from the valve body respectively.[9] In the newer machines proportionating systems like link-25 or O_2 ratio monitor control will be present which will not allow the user to give O_2 less than 25% of the total flow.

Flow meter sub-assembly

This consists of the tube through which the gas flows, the indicator or bobbin or float, a stop at the top of the tube and the scale which indicates the flow.[9] Flow meter tubes are known as Thorpe type and are made of borosilicate glass Pyrex.[8] The tubes either have a single taper or a double taper. When there are separate flow meter tubes for low flows and high flows for the same gas then the tubes are single tapered. If there is a single tube for the gas then it is double tapered. The lower portion of the dual tapered flow tube has a fine taper for measuring low flows and the upper portion has a coarse taper for reading high flows rates.[8]

Indicator also called as rota meter or bobbin or float is present within the flow meter tube which moves up and rotates as the gas flows into the tube. The bobbin is made of aluminium and has an upper rim which is wider than the body. The upper rim contains slanted flutes, which makes the bobbin rotate as the gas strikes the flutes. There is a fluorescent dot over the bobbin making its rotation to be observed easily. The flow tubes and floats are assembled and calibrated together for each specific gas. Therefore if the flow tube breaks, the entire flow meter assembly including the float should be replaced.[14] Sometimes the float may get stuck to the side of the tube as a result of development of static electricity, particularly in dry atmospheres. The effects of static electricity may be reduced by spraying the outside of the tube with an antistatic agent such as croxtine (BOC), which is supplied in an aerosol can.[8]

SCALE

The flow meter scale can be marked directly on the flow tube or to the right of the tube. Gradations corresponding to equal increments in flow rate are closer together at the top of the scale because the annular space increases more rapidly than the internal diameter from bottom to top of the tube.[16]

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:
1. Sight tubes for each gas are individually calibrated at 20°C and 101.3 kPa; they are non-interchangeable.
2. Tubes have different lengths and diameters, and may have a pin-index system at each end.
3. Tubes are leak-proof because of neoprene washers (O-rings) at both ends of the flow meter block.
4. The tubes have an antistatic coating on their inner and outer surfaces. This prevents the bobbin from sticking to the tube wall.
5. The bobbin is visible throughout the length of the tube and has vanes to improve its rotation in the gas flow.[6]

PHYSICAL PRINCIPLES OF FLOWMETERS

The flow meter is of variable orifice type due to the tapering of the tube which has its lower diameter at the bottom. When there is no flow of gas the bobbin rests at the bottom and when the flow control valve is opened the bobbin moves up as the gas flows in. The bobbin floats freely in the tube at an equilibrium position where the downward force on it due to gravity equals the upward force due to the gas flow. The gas flows in the annular opening between the bobbin and the tube. The annular opening around the bobbin increases with the height.[9] The rate of gas flow depends on the three factors:
1. The pressure drop across the constriction is constant for all positions in the tube and is equal to the weight of the float divided by its cross-sectional area.
2. The size of the annular opening - the larger is the size of the annular opening around the bobbin, higher will be the flow.
3. Physical characteristics of the gas - because the annular space is tubular at low flow rates, flow is laminar and viscosity determines the gas flow rate and hence follows the Poiseuille's law. The annular space simulates an orifice at high flow rates, and turbulent gas flow then depends predominantly on the density of the gas and follows the Graham's law.[16]

Since in a variable orifice flow meter there is a mixture of turbulent and laminar flow, for calibration purposes both density and viscosity of the gas are important. Consequently, careful calibration is required if a flow meter is used for a different gas than that for which it was designed.[17] When the anaesthesia machines are used at high altitudes since the density of the gases decreases, when higher flows are set in the flow meters, actual flow of gases will be higher than the set flows, as flow is inversely proportional to the square root of density as per Graham's law.

SEQUENCE OF FLOWMETERS

The position of the flow meters of individual gases is also important. O_2 flow meter should be downstream to all other gases to prevent hypoxic mixture delivered to the patient. As shown in Figure 5, there are 3 flow meter tubes. O_2 is upstream and N_2O being downstream and in between is the third gas like air or CO_2. If there is a break or leak in the middle tube [Figure 6] then part of O_2 will move out through the break in the middle tube and the patient will be getting an hypoxic mixture containing more of N_2O rather than O_2. Instead, if O_2 is downstream [Figure 7a] and N_2O is upstream, then even if there is a leak in the middle tube then patient will get a higher fraction of inspired O_2 which may produce lighter planes of anaesthesia, but not hypoxaemia. Without changing the position of the tubes as in Figure 1, still O_2 can be made downstream of all gases by placing a wedge inside the manifold as shown in Figure 7b.

A leak in the O_2 flow tube may result in creation of a hypoxic mixture even when O_2 is located in the downstream position. O_2 escapes through the leak and N_2O continues to flow towards the common outlet, particularly at high ratios of N_2O to O_2 flow.[16]

LOW PRESSURE SYSTEM

The low pressure system is the part of the machine downstream of the flow meters in which the pressure

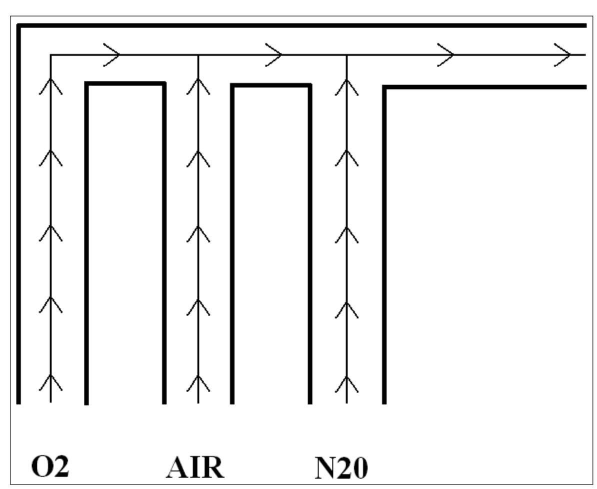

Figure 5: Arrangement of flow meter tubes with oxygen upstream

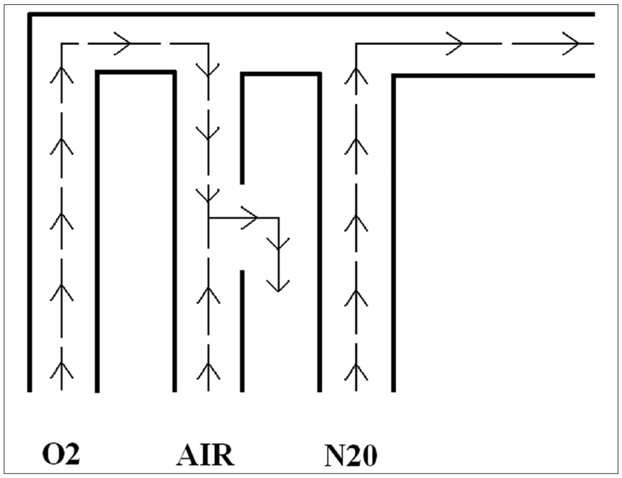

Figure 6: A leak in the middle tube with oxygen flowing out resulting in delivery of hypoxic mixture

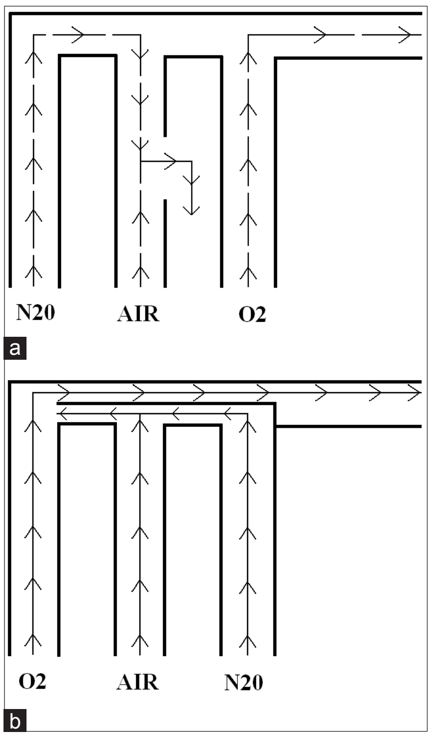

Figure 7: (a) Arrangement of flow meters with nitrous oxide (N_2O) upstream, leak in the middle tube resulting in N_2O flowing out but oxygen flow intact. (b) A wedge in the manifold creating oxygen to be downstream

is slightly above the atmosphere. The components in this system are: (a) Vapourisers mounted on the back bar (b) back pressure safety devices and (c) the common gas outlet.[9] The back bar may terminate in a valve (circuit selector) which turned in one direction permits the use of a semi-closed breathing attachment and in the other passes the gases to a circle absorber. This unit is sometimes combined with a "Trilene Interlock" which prevents the trichloroethylene vapouriser being turned on when closed circuit is in use.[8] Also when trilene vapouriser is turned on, one cannot change over to the closed circuit.

POP OFF VALVE

On anaesthetic machines [Figure 1] with a regulated pressures of 45-60 PSIG there may be a relief valve also called as pop off valve which opens at a pressure of 5 PSIG (300 cm of H_2O) to prevent the risk of damage to the vapourisers and flow meters if the outlet is obstructed.[8]

TABLE TOP SPACE

The pressure regulators and the intermediate pressure circuits are concealed by a metal top for keeping drugs and equipments like Laryngoscope and Endotracheal tubes. Just above the back bar, a table top has been created so that there is a space for keeping the monitors and other equipment.

SUMMARY

Anaesthesia machine introduced by Gwathmey and Boyle nearly 100 years back has had many changes to its original design, mainly to improve the patient safety. However, still the basic structure remains the same. Because of this, a thorough knowledge of the basic design is essential to all the practicing anaesthesiologists and the post-graduate students for safe practice of anaesthesia.

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