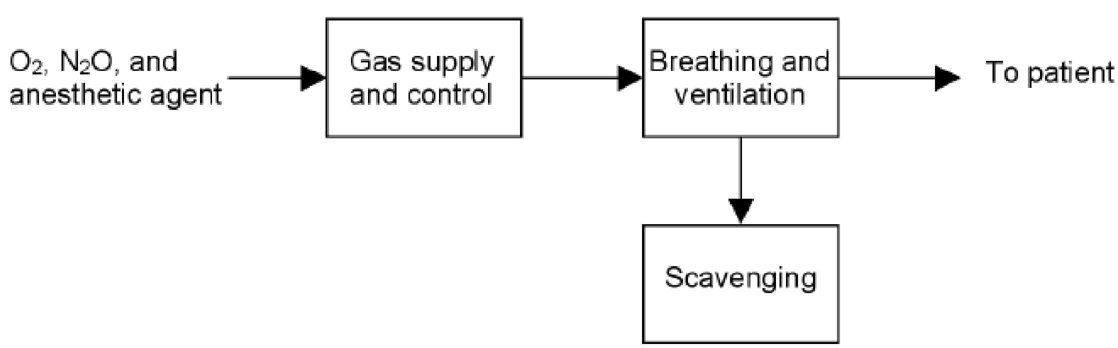
Anesthesia Machine

Introduction:

Although anesthesia has been generally described as the part of the medical profession that ensures that the patient's body remains insensitive to pain and other stimuli during surgical operations, anesthesia is understood as a patient care within four different domains: sedation (reversible patient unconsciousness), relaxation (temporal reduction of the motoric functions of the patient in order to ease the surgical procedures), analgesia (insensitivity to pain), and respiration (granting the respiratory function in order to avoid permanent damage to the different tissues), which has led medical device manufacturers to develop complex machines for anesthesia delivery and patient monitoring. Figure 1, which shows a typical setting found in many operating rooms, includes the equipment required for the delivery of vaporized and intravenous agents in order to allow the proper sedation method for each patient and surgical procedure. The main elements of the anesthesia delivery system illustrated include the gas supply system, the gas mixing subsystem, the vaporizer for inhaled agents, the mechanical ventilator, the breathing circuit of the patient, the absorber for CO2 removal, the infusion pumps required for intravenous anesthesia, and the monitoring subsystem for patient and equipment supervision.



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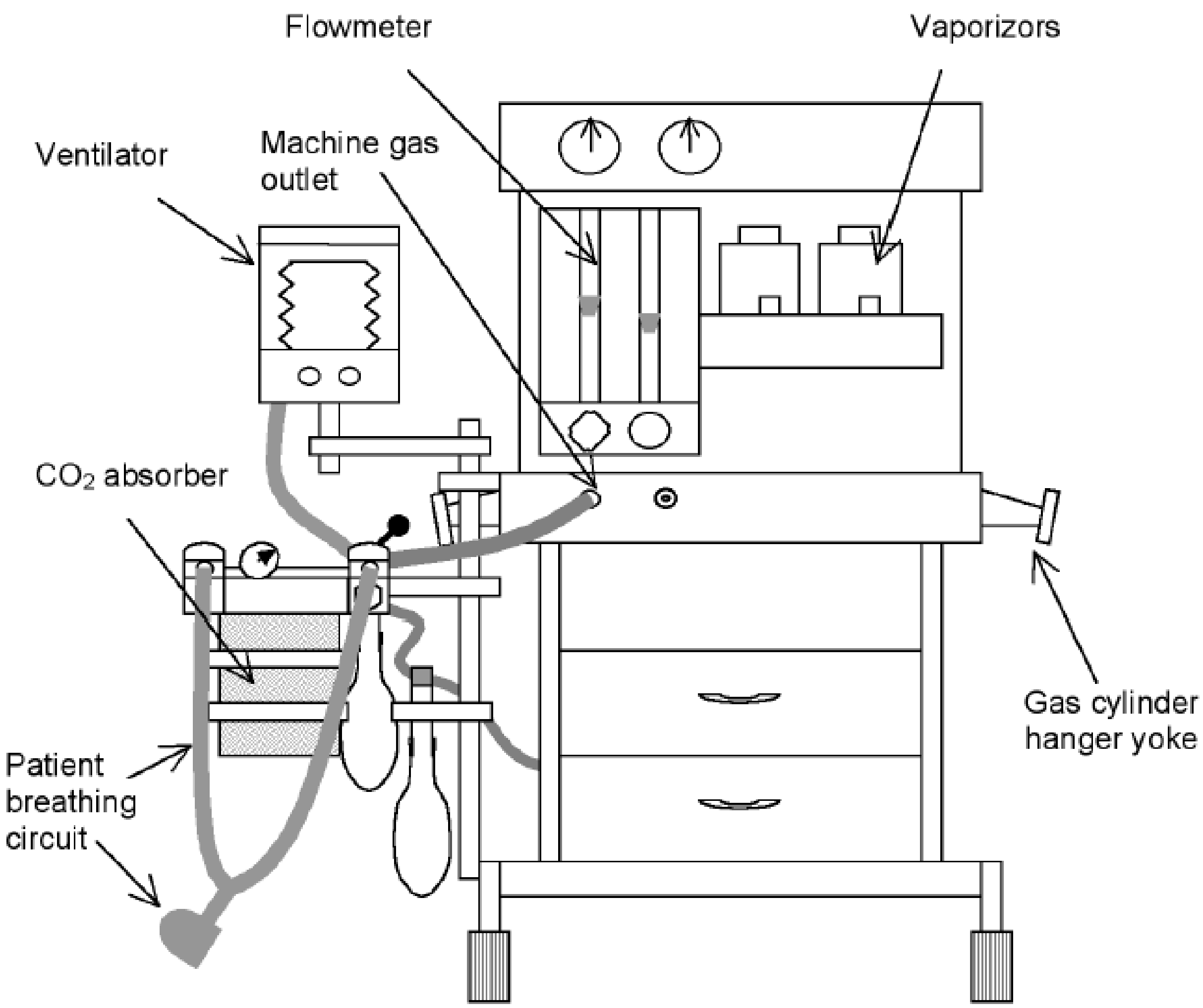
Functional Block Diagram of a Basic Anesthesia Machine



Basic Anesthesia Machine

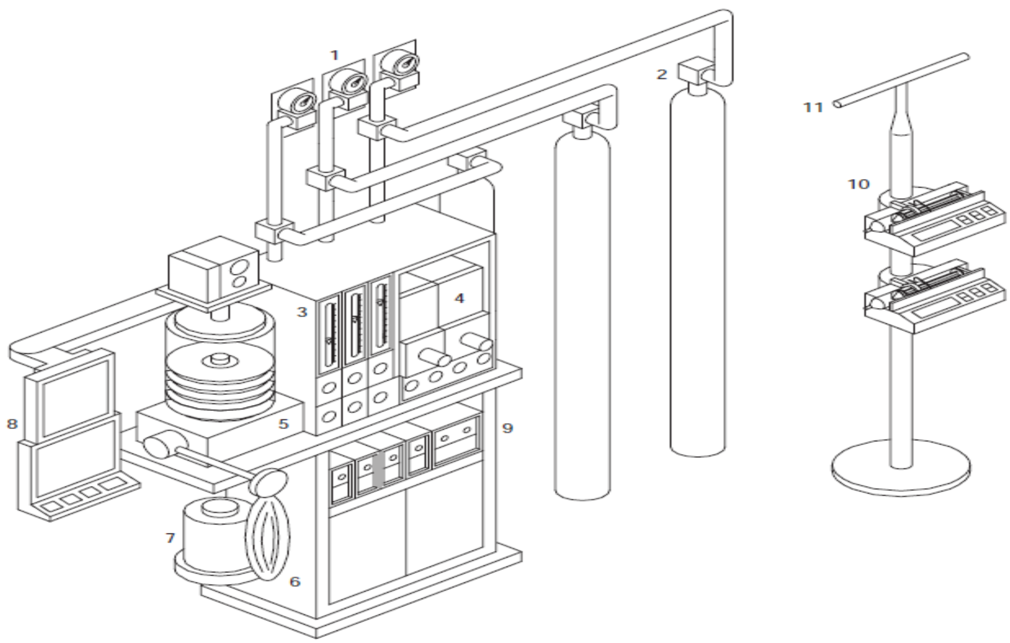


Figure 1. Simplified view of the anesthesia machines in the operating room. (1) Central gas supply (oxygen, nitrous oxide, and air), (2) high-pressure gas cylinders, (3) gas flowmeters and mixing controls, (4) anesthetic agent vaporizers, (5) mechanical ventilator, (6) breathing reservoir bag, (7) absorber for carbon dioxide removal, (8) patient and machine monitors, (9) monitoring amplifier modules, (10) infusion pumps, and (11) standing pole.

Principles of Operation

An anesthesia machine is a device that delivers a precisely-known but variable gas mixture, including anesthetizing and life-sustaining gases. In this sense, anesthesia units dispense a mixture of gases and vapors of known concentrations in order to control the level of consciousness or analgesia of the patient undergoing surgery.
Anesthesia is achieved by administering a mixture of O2, the vapor of a volatile liquid halogenated hydrocarbon anesthetic, and, if necessary, N2O and other gases. As spontaneous breathing is often depressed by anesthetic agents and by muscle relaxants administered in conjunction with them, respiratory support is usually necessary to deliver the breathing gas to the patient.

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For these purposes, the anesthesia machine must perform the following functions:

- Assuring the proper oxygen (O2) flow delivery to the patient.
- Vaporizing the volatile anesthetic agent and blending it into a gas mixture with O2, nitrous oxide (N2O), other medical gases, and air.
- Granting the ventilation of the patient by controlling spontaneous ventilation and using mechanical assistance if needed.
- Minimize the anesthesia-related risk to the patient and the clinical personnel.

In Figure 2, the gas flow supplied by either the pipelines (2) or the security high-pressure cylinders (1) is regulated at the flow meters (5) and mixed in the common gas manifold entering the vaporizer (8), where this mixture is vaporized with the anesthetic agent used. This fresh gas flow is then sent to the patient through the breathing circuit (12), that also collects the expired gas in order to process it through the circuit selected (15). In either case, the gas will pass through the absorber (14) in order to remove carbon dioxide before returning to the inspiratory branch. If mechanical ventilation is used, the ventilator (18) sets the inspiratory and expiratory cycles according to the control adopted.

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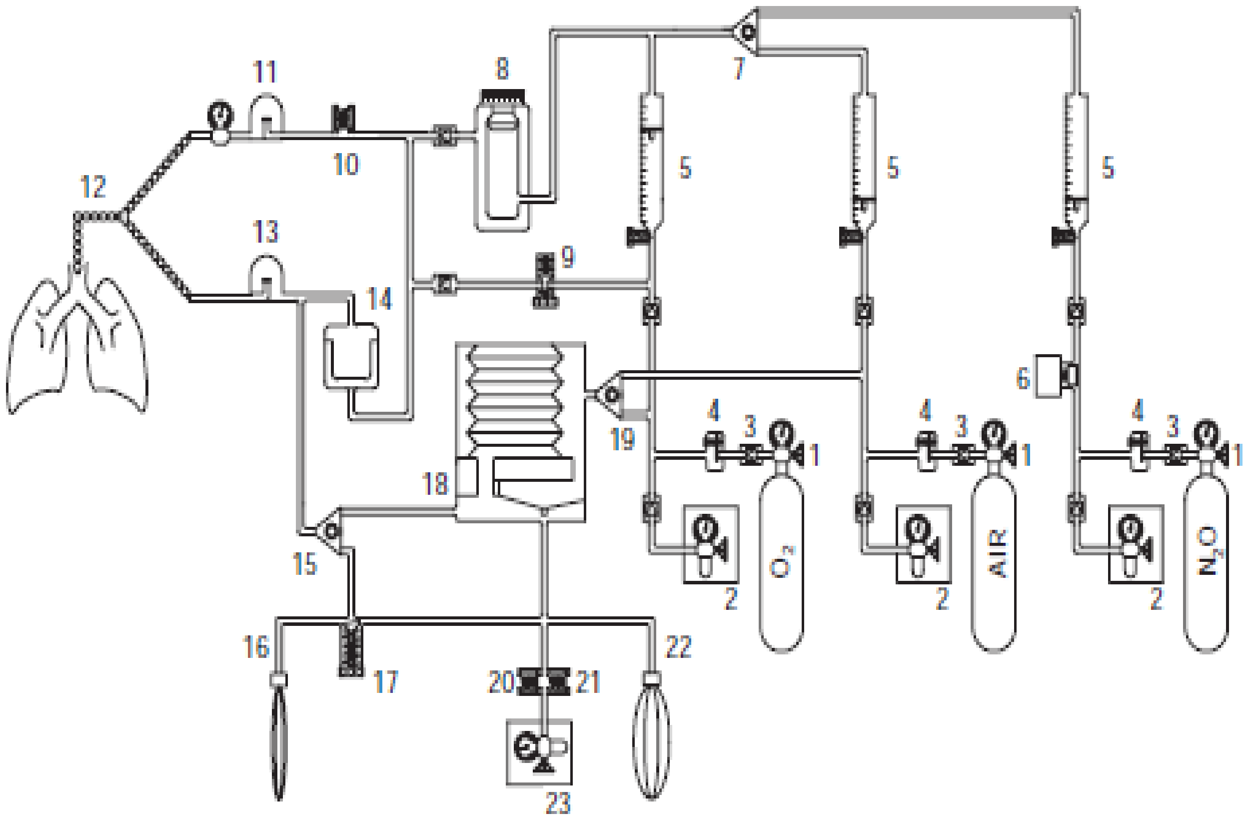

Figure 2. Schematic diagram of an anesthesia machine for the delivery of inhaled agents. (1) High-pressure gas cylinder, (2) central gas supply outlet, (3) unidirectional-flow valve, (4) pressure regulator, (5) gas flowmeter, (6) fail-safe device, (7) carrier gas selector, (8) vaporizer, (9) oxygen flush valve, (10) fresh gas flow positive pressure relief valve, (11) unidirectional inspiratory valve, (12) patient breathing circuit, (13) unidirectional expiratory valve, (14) carbon dioxide absorber, (15) mechanical ventilation or spontaneous breathing circuit selector, (16) breathing reservoir, (17) adjustable pressure limiting valve or pop-off valve, (18) mechanical ventilator, (19) ventilator driving gas selector, (20) scavenging gas positive pressure relief valve, (21) scavenging gas negative pressure relief valve, (22) scavenging reservoir bag, and (23) central vacuum inlet.

In the case of spontaneous ventilation, the exhaled gas is scavenged through an adjustable pressure limiting valve (APL) to the available waste gas removal system (23).

From the description related above, the anesthesia machine may be understood as the ensemble of the following subsystems:

- Gas supply
- Flow Regulators
- Vaporizer
- Breathing system
- Scavenging system

Gas Supply System

As mentioned above, anesthesia machines do not just administer the anesthetic agents but also life-sustaining gases, such as oxygen and nitrous oxide (that may be substituted by medical air or helium, among others), so that dedicated systems have been developed for precisely supplying the proper concentration of these gases to the patient. In this sense, the gas supply system relies on three different components: the gas source, the flow regulators, and the associated safety devices.

Gas Sources

The gases commonly used in anesthesia (oxygen, nitrous oxide, and compressed air) are under high pressure and may be piped in from a central storage area or used directly from nearby compressed gas cylinders in case of central supply failure (4–9).

Central Gas Supply

Air is produced and distributed from a compressor plant on-site. These gases are usually supplied at **345KPa (50 psi)** after a two-stage regulation from the nominal pressure of the tanks. **The wall outlets (2) are usually suited** with primary and secondary check valves (that prevent reverse flow of gases from machine to pipeline or atmosphere), a pressure regulator, and a filter for the removal of the impurities.

Gas Cylinders

In case of central supply failure, the anesthesia machine should be fitted with a backup source of medical gases in order to grant continuous ventilation to the patient, which has become mandatory in most countries where the use of backup gas cylinders is specifically included within the regulations related to anesthesia machines. For this purpose, it is advisable to include cylinders for oxygen and nitrous oxide delivery.

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These compressed gas cylinders (which are mounted on yokes attached to the anesthesia machine) use a filter, and unidirectional flow check valve, a pressure regulator, and gauge. The pressure regulator **(4)** is needed to set the gas pressure below the pipeline supply pressure (310KPa for the cylinders) in order to prevent recirculation of the gas from the cylinders to the central supply system. Aside from this pressure regulator, cylinders usually include additional security features such as a safety relief device consisting of a frangible disc that bursts under extreme pressure, a fusible plug made of Wood's metal that has a low melting point, a safety relief valve that opens at extreme pressure.

Safety Devices

In order to prevent damage associated with hypoxic ventilation, several safety devices are included within the anesthesia machine. The hypoxic Guard system links the controls of O2 and N2O in order to avoid the administration of hypoxic gas mixtures (mixtures containing less than 25% oxygen). This system is complemented by means of the so-called fail-safe device (6), which shuts off the nitrous oxide supply when the oxygen pressure at the flow meter falls below a certain threshold value, which typically ranges from 69KPa (10 psi) to 138KPa (20 psi). Additionally, an oxygen flush valve (9) must be included in order to allow the rapid (35–75 L/min) washout of the breathing circuit in case of emergency, as this valve directly injects oxygen into the patient without passing through any kind of vaporizer (4–9).

Flow Regulators

Anesthesia machines have included independent flow controls for each of the medical gases used in order to cover the requirements of the anesthesiologist for precisely controlling the amount of each gas flowing into the breathing circuit attached to the patient. These flow meters (5) typically consist of a glass tube in which a floating conical element rotates at different heights as a function of the flow streaming out from the meter. Although modern machines have included electronic flow meters based on different sensing principles (ultrasound Doppler, electromagnetic sensing, etc.) and digital displays, it is advisable to include at least one conventional glass flow meter in order to allow operation even when electrical power fails.

Vaporizer System

In order to deliver most of the inhaled anesthetic agents through the breathing circuit, these liquid substances must be vaporized into the carrier gas stream. To achieve this goal, special devices have been developed and, today, are considered one of the most important elements found in anesthesia machines. A vaporizer enriches the carrier gas mixture with a vapor fraction of the volatile agent by means of different principles, leading to different families of these devices such as those known as variable bypass, heated blender, measured flow, and the recently introduced injectors. The most common are shown in Fig.1.

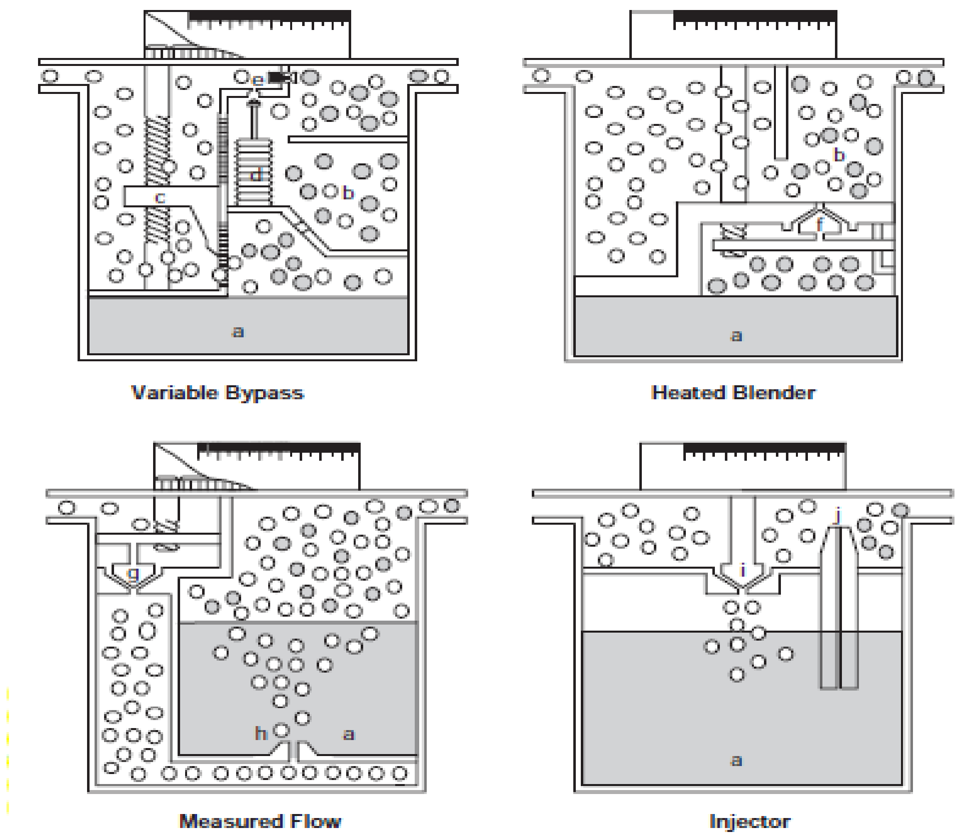

Figure 3. Idealized views of different types of vaporizers. (a) Liquid agent, (b) mixing chamber, (c) bypass valve, (d) temperature compensation bellows, (e) pressure relief valve, (f) feedback-controlled metering valve, (g) constant flow valve, (h) gas mixture bubbler, (i) bypass valve, and (j) injector

Variable Bypass

The variable bypass vaporizer is the most commonly used in today’s machines for the vaporization of many agents such as enflurane, isoflurane, halothane, and sevoflurane. This type of vaporizer receives this name because a variable shunt valve (c in Fig. 3) regulates the proportion of gas flowing into the vaporization chamber and into the mixing chamber (b). As the gas flowing out of the vaporizer chamber is mixed with the bypassed gas stream, the concentration of the agent in the gas mixture is directly related to the splitting ratio of the valve. Temperature compensation bellows (d) are included in order to compensate for the effect of temperature changes that affect the equilibrium vapor pressure above the agent. As this kind of vaporizer is able to deliver accurate concentrations of the anesthetic agent, specific designs and calibration methods are used for each type of liquid agent.

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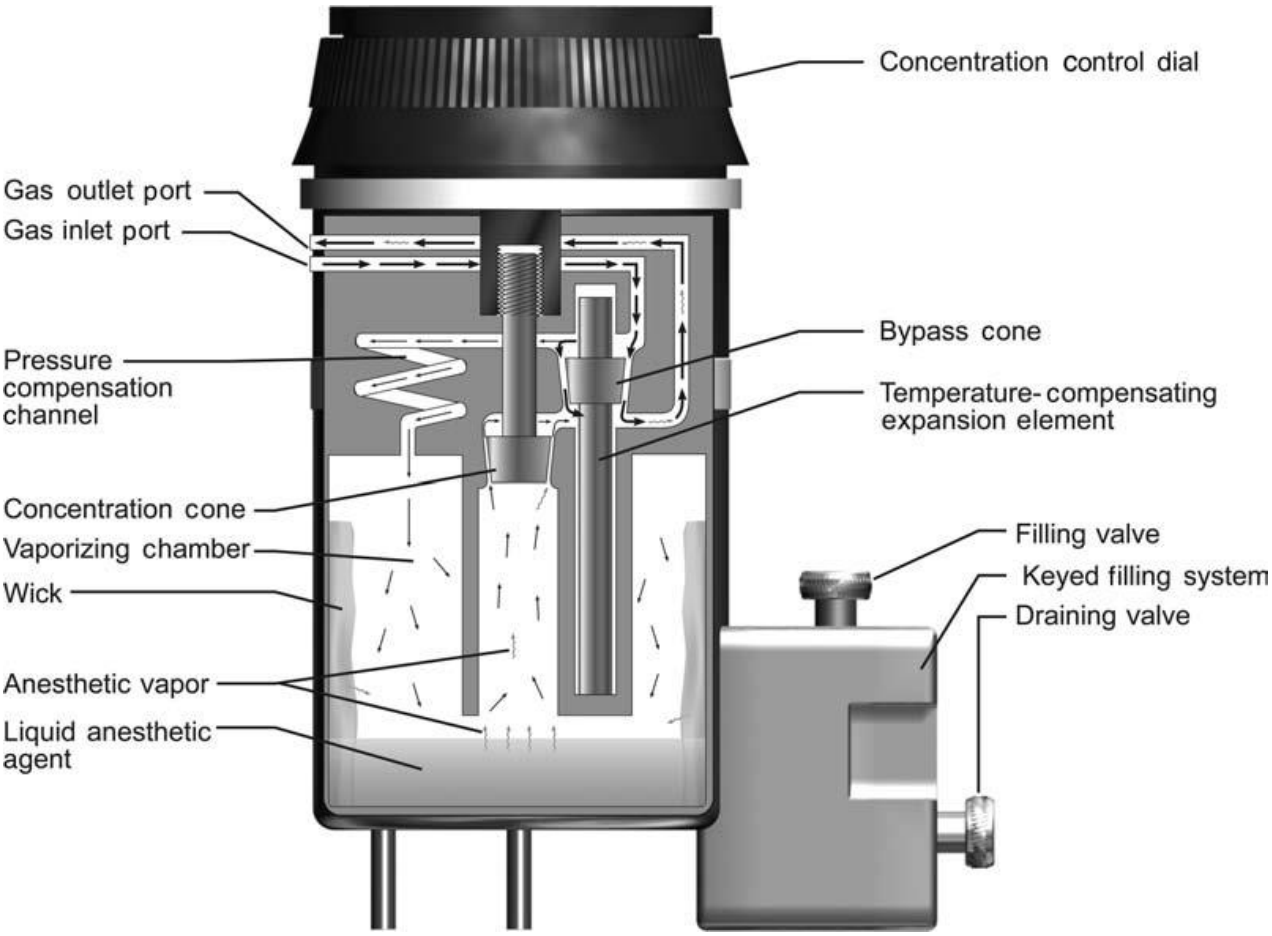

Figure 2. Schematic of a variable-bypass vaporizer. Arrows indicate direction of gas flow; heavier arrows indicate larger flow rates. Gas enters the Inlet Port and is split at the Bypass Cone into two streams. One stream is directed through a bypass channel and the rest enters the Vaporizing Chamber. Gas entering the Vaporizing Chamber equilibrates with Liquid Anesthetic Agent to become saturated with Anesthetic Vapor. This concentrated anesthetic mixture exits the chamber to join, and be diluted by, gas that traversed the bypass channel. The Concentration Control Dial is attached to the Concentration Cone, which regulates resistance to flow exiting the Vaporizing Chamber and thus controls the anesthetic concentration dispensed from the Outlet Port.

Heated Blender

Initially introduced for use with desflurane, the liquid agent is heated within a chamber before entering the mixing chamber through an adjustable feedback-controlled metering valve (f) that regulates the vapor stream flow.

Measured Flow

These devices are not able to deliver accurate concentrations of the liquid agent because they are not calibrated, which is because of the vaporization control implemented, which is based on a constant flow of carrier gas (g) bubbling up (h) through the liquid agent.

Injector

This recently introduced system uses a valve (i) to regulate the amount of fresh gas flowing into a pressurized chamber where the liquid agent is stored. As the pressure of this chamber increases, the agent is forced up through the injector nozzle (j) where it is atomized within the fresh gas flow. As no vaporization occurs, (just atomization of the liquid agent), temperature compensation is not required.

Breathing System

Once the anesthetic agent is vaporized at the desired concentration, the gas mixture has to be administered to the patient in order to get the desired therapeutic effect and the proper ventilation. For this purpose, anesthesia machines are connected to the patient by the so-called breathing circuits.

Breathing circuits are often classified either as open systems or closed systems. In open systems, the fresh gas flow is administered to the patient before being scavenged, whereas in closed systems, the exhaled gases are processed in order to recycle them, reducing the total amount of agent required (in order to reduce anesthesia costs and staff exposure to the agents.

Circle System

The breathing circuit receives the vapor-enriched gas mixture from the vaporizer outlet and sends it to the patient circuit (12) through the unidirectional inspiratory valve (11), installed to prevent rebreathing from the patient to this branch of the circuit. The inspired branch is completed with a security overpressure valve (10) installed in order to release the gas out of the circuit in case the pressure of the gas mixture going into the patient circuit exceeds the threshold of 12.5 kPa (125 cm H_2O) established by the regulating authorities. The exhaled gases return through the unidirectional expiratory valve (13) flowing into the absorber (14), which is installed to remove carbon dioxide in order to recycle the breathing gas. In the function of the circuit selected (15), part of the exhaled gases will cycle through the ventilator (18) or the spontaneous breathing circuit formed by the breathing reservoir bag (16) and the adjustable pressure limiting valve (APL) (17) before returning to the absorber inlet.

Carbon Dioxide Absorber

Circle systems require the use of chemical elements for carbon dioxide removal from the exhaled gases before recycling them back to the inspiratory limb of the breathing circuit. These absorbers present in the form of a canister containing pellets of the absorbing compound (soda lime), which is placed within a shell connected inline with the circle system.

Ventilation

Ventilation of the patient should be granted for the supply of the life sustaining gases and the vaporized anesthetic agent, which is usually done in two ways, depending on the ventilator assistance strategy adopted. If the patient presents a healthy condition and the surgical procedure does not interfere with the function of the respiratory system, the anesthesiologist in charge of the sedation may decide for keeping spontaneous ventilation throughout the procedure instead of mechanical ventilation. If the first strategy is adopted, the patient will breathe spontaneously inhaling the gas mixture through the inspiratory limb of the circuit before exhaling the mixture to the expiratory one. As the gas is expired, it enters into the reservoir bag (16) connected to the pop-off or adjustable pressure limiting valve (17), which is sensitive to the pressure of the exhaled stream. In case this pressure exceeded the preset level, the APL valve will open, sending a fraction of the exhaled gases directly to the scavenging system. If mechanical ventilation is used, a similar valve located at the ventilator will release the excess pressure to the scavenging system, assuring the proper operation of the machine.

Scavenging System

Once the gas mixture has been released by the ventilation circuit, it must be properly disposed in order to avoid the risks associated with the contamination of the operating room's atmosphere. For this purpose, most of the hospitals count on central scavenging systems based on vacuum pipelines.

In order to guard the patient airway from possible suction by the scavenging system, modern systems include pressure relief valves. If the suction pressure was greater than the pressure of the exhaled gas stream, the negative pressure relief valve will open, letting the air from the operating room flow into the scavenging system until the pressure of the line reaches the preset value of the valve.

In the opposite case, when the suction pressure was not enough to assure the disposal of the exhaled gases, a positive pressure relief valve will open, ejecting the exhaled gas mixture into the atmosphere of the operating room.

This system, based around valves between the anesthesia machine and the scavenging system, is known as a closed system since the introduction of the first open systems in recent years. In these other systems, which have become popular, the exhaled gases are scavenged from a dedicated reservoir bag without requiring pressure relief valves.

Monitoring

In addition to the main components described above (gas delivery, vaporizer, ventilator, and breathing circuit), anesthesia machines usually include a monitoring subsystem specifically designed for the supervision of the state of the patient and the proper function of the whole system in order to:

1. Improve the security of the patient as a whole by preventing potentially harmful physiological conditions and detecting malfunctions in the normal operation of the anesthesia delivery unit.
2. Collect several physiological measures, which are considered to be interesting by the specialist in charge of the anesthetic procedure.
3. Check the integrity of the different components involved in anesthesia administration and taking corrective actions in response to system malfunctions.
4. Study the degree of change on a certain indicator in order to analyze trends and provide data required for the forecast of the patient evaluation during the surgical procedure.
5. Validate the impact of a specific therapy on the physiological state of the patient in order to give personalized anesthetic care.

Anesthesia Delivery System Supervision

System failures or malfunctions (such as hypoxic gas mixture administration, poor ventilation of the lungs because of low-volume gas mixture supply, or misconnections in the administration piping, overdosing, etc.). Seriously endanger patients undergoing the anesthetic procedure. In order to avoid the undesired effects of these failures, granting the proper operation of the anesthesia delivery unit, several variables should be monitored, such as:

- Inspired oxygen concentration.
- Anesthetic vapor concentration.
- Carbon dioxide concentration.
- Air pressure.
- Exhaled gas volume.
- Manually operated valves and regulators set-points.

Gaseous Concentrations

Oxygen concentration has to be continuously monitored in order to reduce the risk of administration of hypoxic or hyper oxygenated gas mixtures. Delivery of inappropriate gas mixtures should trigger the proper alarming mechanism. Although most of the devices limit the minimum rate of oxygen to a minimum of a 25%, inspired oxygen concentration has to be sensed at the inhalatory branch of the breathing circuit by means of transducers.

Patient Monitoring

As happens in most of the medical procedures, anesthesia should minimize the patient's perception of pain while preserving the normal functionality of all of the body systems. In order to grant the integrity of the patient, certain physiological parameters should be monitored to correct possible alterations before they lead to permanent cellular damage. In this sense, monitoring the oxygenation using pulse oximeter, ventilation, circulation, temperature, blood pressure, ECG, and neurological function of the patient using EEG is mandatory when performing anesthetic procedures. Among others, typical anesthetic protocols include the acquisition of hemodynamic, respiratory, and neurological variables.

Monitoring the Depth of Anesthesia

Brain stem auditory evoked responses have become the closest to depth of anesthesia monitoring, but it is difficult to perform، is expensive, and is not possible to perform during many types of surgery. A promising new technology، called bi-spectral index (BIS monitoring) is purported to measure the level of patient awareness through multiple analysis of a single channel of the EEG.