The principles of anaesthetic vaporizers

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Abstract

Fluorinated hydrocarbons have transformed inhalational anaesthesia, and vaporizers are essential for safe and accurate delivery of these agents. The modern day vaporizers have evolved considerably since the ether inhaler invented by John Snow in 1847 and are robust, precise and efficient. For an anaesthetist to administer safe inhalational anaesthetic, it is important to understand the physical principles of the various inhalational anaesthetic agents along with the working principles of the vaporizers. Almost all modern vaporizers are located outside the circle system and the have multiple safety mechanisms in place.

Keywords Aladin cassette; desflurane; Dräger DIVA®; draw over; measured flow; plenum; sevoflurane; vaporizer; vapour pressure; variable bypass

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Learning objectives

After reading this article, you should be able to:

- outline the key properties and characteristics of anaesthetic vapours and gases
- understand the relevant principles of anaesthetic vaporizers
- recognize and understand the factors affecting the vaporizer output

Introduction

A vaporizer is a device which can accurately deliver a desired amount of inhalational agent in the form of a vapour.

In the past this has ranged from simple masks to uncalibrated and variable output devices, such as the Schimmelbusch mask which was used to administer ether and chloroform. Modern vaporizers are extremely accurate microprocessor-controlled devices that can safely add a precise and adjustable concentration of vapour to the fresh gas flow (FGF). They are agent specific and capable of delivering a constant concentration of agent regardless of temperature changes and flow through the vaporizer. Vaporizers have evolved both to cater to the properties of new inhalational anaesthetic agents and also as solutions to the problems and limitations of early vaporizers.

Physical properties

Inhalational agents are presented as a liquid at room temperature, yet their delivery requires the agents to be in gaseous form. In any liquid, some of the molecules will have sufficient energy to change state and turn into gaseous form, becoming a vapour. Every substance has a *critical temperature* (Figure 1) above which it can only exist as a gas, regardless how much pressure is applied. At or below this temperature, it can exist in both liquid and gaseous form. A vapour is a gas that exists below its critical temperature.

Usually when energy is added to any substance, this increases its temperature. Similarly, when a substance that is at a higher temperature than its surroundings cools down, it transfers heat to its surroundings. Therefore we could say that there is a change in the temperature of a substance when there is flow of energy between the substance and its surroundings. When there is a change in the physical phase of the substance without change in temperature, for example change of a liquid to its gaseous form, the energy required to produce this change is called the *latent heat*. This can also be called the hidden or dormant heat. Latent heat of vaporization (LV) is the latent heat required to convert a unit mass of a substance from liquid to gas. The latent heat of vaporization of water is 2260 kJ/kg.

When a liquid is in a closed container, the vapour molecules constantly collide against the walls of the container and the surface of the liquid exerting pressure, with some vapour molecules re-entering the liquid phase. At any given temperature, when there is equilibrium between the amount of vapour leaving and entering the liquid, the vapour is termed saturated. The pressure that is exerted by the vapour when it is in equilibrium with the liquid state is known as the *saturated vapour pressure* (SVP). Increasing the temperature of the system increases the SVP. The SVP is constant for a volatile anaesthetic at a given temperature (usually measured at 20°C) and is independent of atmospheric pressure. The *boiling point* of an anaesthetic agent can be defined as the temperature at which the SVP equals the atmospheric pressure.

As the high-energy molecules (the vapour particles) leave the system, so does the energy stored in these particles such that the average temperature of the remaining liquid will fall. As a consequence, the SVP will also fall.

Volatile anaesthetics are presented as liquids, and these liquids can produce large quantities of vapour. For every 1 ml of liquid volatile anaesthetic, approximately 200 ml of vapour is produced (Table 1).

The minimum alveolar concentration (MAC) is a measure of anaesthetic agent *potency*. It is defined as the minimum alveolar concentration of anaesthetic at 1 atmosphere (approx. 100 kPa) which produces immobility in 50% of subjects on exposure to a noxious stimulus. At their SVP, most anaesthetic agents are very potent. Sevoflurane has an SVP of approximately 22 kPa at 20°C and a MAC of about 2%. Hence, if sevoflurane is fully saturated at atmospheric pressure, the concentration would be 22% which

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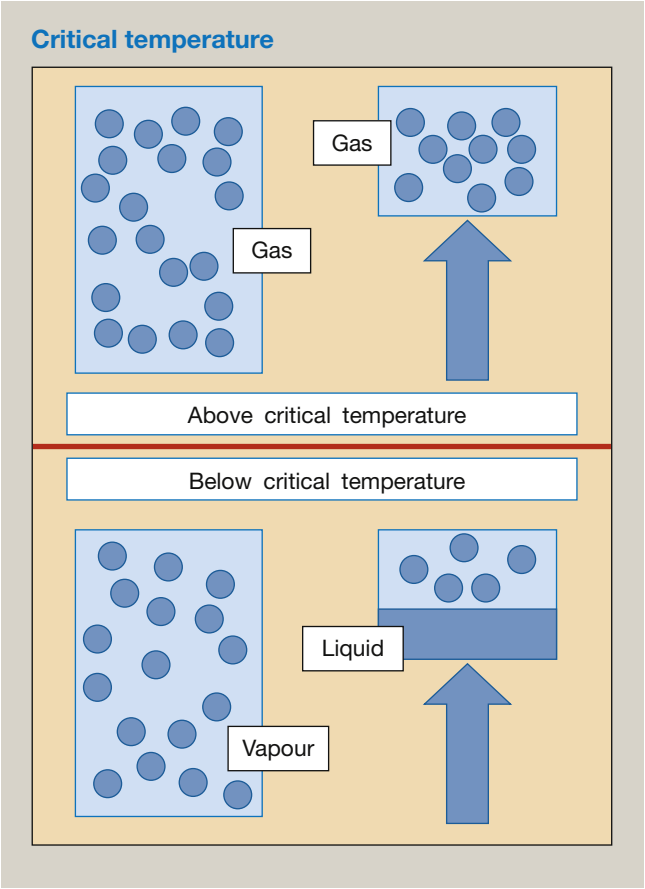

Figure 1

is roughly 11 times more potent than 1 MAC. Therefore, vapours must be diluted to provide clinically meaningful concentrations and the way this is done forms the basis of the vaporizer classification as shown in Figure 2.

Variable bypass vaporizers (Figure 3)

Variable bypass vaporizers can be draw over, plenum or plenum with electronic control.

Draw over vaporizers use fresh gas flows driven by the patient's respiratory effort. These vaporizers are low-resistance, lightweight and can be used without access to compressed gas. This makes it ideal for use in the military setting or in low income developing countries where access to compressed gas may be limited or expensive. Different inhalational agents can be used,

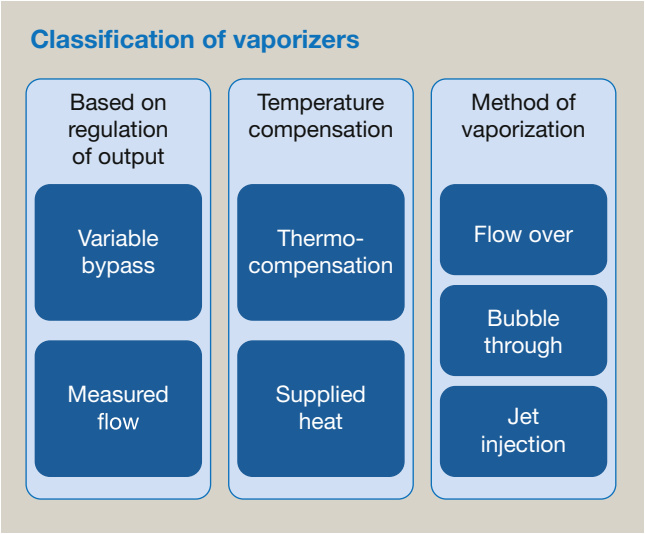

Figure 2

and the machine recalibrated by attaching the appropriate scale to the variable bypass lever. Examples of draw-over vaporizers include the Oxford Miniature Vaporizer (OMV) or the Diamedica Draw-Over Vaporizer (DDV, Diamedica Ltd, Bratton Fleming, UK)

Plenum vaporizers have two possible paths for FGF through the vaporizer with the amount going through each path dependent on the concentration set on the vaporizer dial which controls the splitting ratio. The splitting ratio describes the proportion of gas going via the vaporizer chamber compared to going into the bypass channel. Examples of plenum vaporizers include the Boyle's bottle and the Dräger D-Vapor® and Tec® vaporizers.

Plenum vaporizers are more accurate than draw-over vaporizers as they maintain a more accurate SVP by temperature compensation. However, these changes increase the internal resistance, requiring a driving pressure of fresh gas above the atmospheric pressure and making them unsuitable to be placed as a vaporizer in circuit.

The Aladin cassette

The Datex-Ohmeda Aladin™ cassette (GE Healthcare) consists of the cassette (the agent-specific vaporizing chamber) and a central processing unit (CPU). It is an electronically controlled plenum vaporizer. The cassette is unique to an individual anaesthetic agent and is also interchangeable, allowing a new

Properties of anaesthetic agents

Agent	Boiling point (at 100 kPa) °C	SVP (at 20°C) kPa (mmHg)	MAC (vol %) in 100% O_2	Vapour output/ml of liquid
Halothane	51	31.9 (243)	0.75	211
Isoflurane	48	31.5 (240)	1.15	182
Sevoflurane	58	21.3 (160)	2	170
Desflurane	23	88.5 (669)	6	193

Table 1

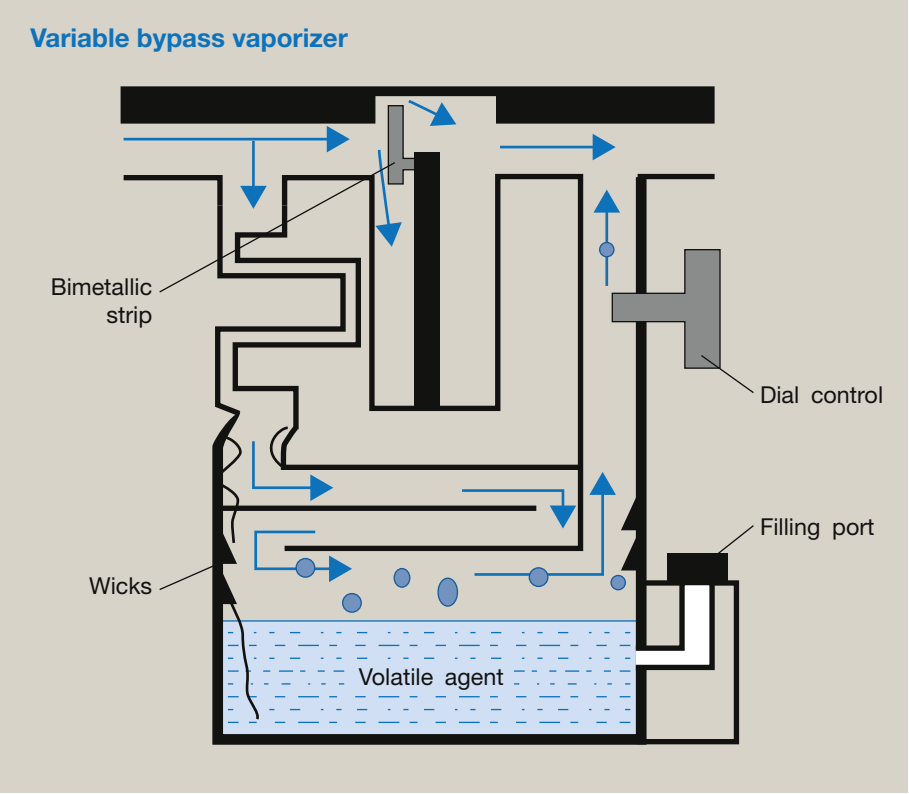

Figure 3

anaesthetic agent to be delivered to the patient. However, the machine only accepts one cassette at a time. Desflurane can be administered by the Aladin cassette. The splitting ratio is controlled by the CPU and the flow through the valve is governed by a number of variables; the setting on the dial, the temperature and pressure in the cassette, gas flow into the bypass and vaporizer channel and the carrier gas composition. The bypass and vaporizing channel gas flows reunite in a mixing chamber which reduces the effect from back pressure. One-way and spring-loaded valves prevent overfilling and leakage of the volatile agents. The Aladin cassette can provide on screen data of anaesthetic usage and remaining levels, but the system requires electrical power to function.

Measured flow vaporizers (Figure 4)

Measured flow vaporizers have a different mechanism of action compared to variable bypass. Rather than the gas being split into two separate channels, measured flow vaporizers have a separate stream of pressurized gas which is added to the FGF. To maintain a constant output, the vaporizer measures and adjusts the delivery to the agent based on the FGF. The earliest form of this type of vaporizer was the copper kettle and this pioneering model forms the forerunner to the modern forms of Tec 6 and cassette-based vaporizers.

Desflurane vaporizer

In the 1990s, Datex-Ohmeda (GE Healthcare) developed the Tec 6™ vaporizer which was designed to be specifically used with desflurane. Desflurane has an SVP three to four times that of the

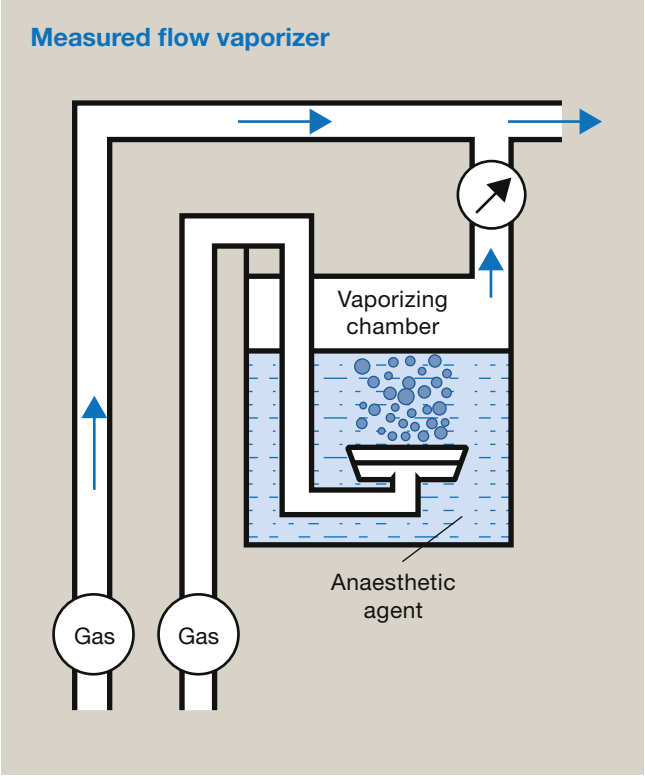

Figure 4

other anaesthetic agents and also has a low boiling point (23.5°C). At room temperature, in a standard vaporizer, the agent would intermittently boil with great fluctuation in vapour production. Desflurane is therefore heated to 39°C so that a stable SVP is produced. In heating the desflurane, the pressure within the vaporizer increases to around 2 atmospheres, providing a driving pressure to add the agent to the gas flow to the patient. Heating provides a solution to another physical property of desflurane. Given its high SVP (88.5kPa at 20°C or 194kPa at 39°C), if desflurane was used in a plenum vaporizer a high volume of fresh gas flow would be need to dilute the gas to a clinically useful concentration. However, the design of the vaporizer means that the agent is added directly to the fresh gas flow (FGF) with an automatic control to adjust the delivery of desflurane based on the gas flow. The flows are detected through pressure transducers, which adjust the vapour output to match the FGF and maintain an accurate concentration output.

Direct injection of vapour anaesthetic (DIVA)

The direct injection of vapour anaesthetic (Drager DIVA® or Maquet 950® series) are other examples of measured flow vaporizers which can be used for all inhalational agents. The vaporizing module is agent specific, and the anaesthetic agent enters the evaporation chamber by a closed feedback loop. Once in the evaporation chamber, the SVP of the liquid anaesthetic is produced and this gas is directly injected either into the gas flow to the patient or through a mixing chamber before entering the fresh gas flow. The chambers are all controlled by one way valves to prevent back flow. A CPU monitors the amount of volatile in the vaporizing chamber, the FGF and the target expired volatile concentration to regulate the volume of anaesthetic agent delivered. The vaporizer compensates electronically for increases in the fresh gas flow by increasing the amount of volatile injected.

Factors that influence carrier gas SVP

Fresh gas flow

Gas leaving the vaporizer chamber needs to be fully saturated in vapour and the modern plenum vaporizer is specifically designed to allow for this regardless of any changes in FGF. Plenum vaporizers use wicks, cowls and other methods that increase the surface area of contact between the vapour and fresh gas which ensures complete saturation. Thorough testing has evidenced appropriate accuracy between the flow rates of 0.25 L/min to 15 L/min.

Temperature

Temperature changes within the vaporizer will affect the SVP. As vaporization proceeds, it uses energy which is supplied as a loss of heat from the liquid. Unless there is a compensation for the loss of heat, the drop in liquid temperature will decrease the vapour pressure within the vaporizer. There are two methods of compensation:

Thermostabilization: the required heat is supplied by a heat sink, usually a metal jacket built into the construction of the modern vaporizer. A metal such as copper, with a high thermal conductivity and high specific heat capacity, is used as it can buffer the changes in the temperature between the vaporizing chamber and the atmosphere. The high thermal conductivity makes it easy to transfer ambient heat from the surroundings to the vaporizer and the high thermal capacity enables it to absorb and store heat from its surroundings.

Thermocompensation: in the newer and more widely used 'TEC' series vaporizer, temperature compensation is achieved by way of a bimetallic strip. This strip made of two different metals with differing thermal coefficients controls the fresh gas flow into the vaporizer. As temperature within the vaporizer falls, the metallic strip bends allowing more fresh gas into the vaporizing chamber.

Pumping effect (back pressure)

Intermittent positive pressure ventilation or use of the oxygen flush can generate a retrograde pressure on the vaporizer, called pumping effect. As a consequence of the pumping effect, some of the gas that in the vaporizer is forced back into the vaporizer and bypass channel. The concentration of anaesthetic vapour in the bypass channel will increase, and when reunited with the gas from the vaporizer chamber, can lead to delivery of an inaccurate or higher concentration of anaesthetic agent. This effect is more obvious during low-flow anaesthesia, high inspiratory pressures or when the levels of the anaesthetic agent within the vaporizer are running low.

The present-day vaporizers are fortunately not vulnerable to this occurrence as they have inbuilt design features that help offset this effect. This includes a long serpentine inlet tube to the vaporizer, a non-return check valve at the outflow end and reducing the size of the vaporizing chambers compared to earlier vaporizers.

Altitude

Plenum vaporizers are calibrated at sea level. The SVP in the vaporizing chamber is unaffected by changes in the ambient pressure. Therefore as altitude increases and the ambient pressure declines, the partial pressure of the anaesthetic agent within the vaporizing chamber remains constant. However, changes in barometric pressure will affect the carrier gas composition passing through the vaporizer, which in turn will affect the concentration of vapour in the mixture leaving it. At lower atmospheric pressures, the number of molecules of carrier gas travelling through the bypass channel is reduced but not the number of molecules leaving the vaporizing chamber. This will lead to an increase in the volume per cent concentration of the agent at the outlet. Since the depth of anaesthesia is based on the brain partial pressure, which remains unchanged, this increased concentration is clinically not significant.

Safety features of vaporizers

The newer anaesthetic vaporizers have evolved to incorporate safety features to minimize hazards. Early vaporizers had to be kept upright so that the liquid anaesthetic agent would not enter the breathing circuit and deliver potentially dangerous levels of volatile. Anti-spill mechanisms and secured vaporizers minimize this risk. Vaporizers cannot be over-filled and colour-coded adapters and keyed fillers prevent the vaporizers being filled with the wrong agent. Interlocks (e.g. the Select-a-Tec

mechanism by Ohmeda) prevent the administration of more than one inhalation agent by extending a lateral rod when a vaporizer is switched on, stopping the operation of the other vaporizers.

New developments

Vaporizer for sedation

The AnaConDa© (Sedana Medical) is an in-circuit vaporizer designed for sedation in intensive care where exhaled volatile anaesthetic is absorbed and returned to the patient. A syringe pump delivers volatile anaesthetic (sevoflurane or isoflurane) into the device where is it vaporized and delivered into the circuit. The flow of liquid anaesthetic into the circuit is set manually and titrated based on clinical effect and monitoring the volatile agents. During expiration, air and carbon dioxide passes through the active carbon filter into the ventilator exhaust. Exhaled volatile remains within the active carbon medium. During the next inhalation, the volatile within the active carbon is desorbed and passed back into the patient with air and oxygen, along with more volatile from the evaporator.

The movement of volatile is driven by either the patient's respiratory effort or an ICU ventilator. A separate gas sampler is required to analyse inhaled and exhaled volatile agents. The vaporizer is placed between the endotracheal tube and the Y-piece but is single use and lasts 24 hours. It does increase the dead space and resistance within a circuit and can hinder elimination of carbon dioxide.

Summary

The accuracy and safety of vaporizers has greatly improved over many years through many technological advances. Through these advances, volatile anaesthesia has become more titratable and more economical Newer methods of delivering volatile anaesthesia, may extend the boundaries of volatile anaesthesia out of the theatre suite into other areas. ◆

FURTHER READING

Davey Andrew J, Diba Ali. Ward's anaesthetic equipment. 6th edn. Saunders, 12 Dec 2011.

