Understanding vaporizers

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Revalidation FOR ANAESTHETISTS
RCA Revalidation matrix
Matrix reference 1A03

Key points

Vaporizers allow a known and reproducible concentration of anaesthetic vapour to be delivered in a safe and reliable manner.

An understanding of the physical properties of anaesthetic agents is required to appreciate the design of modern vaporizers.

Plenum vaporizers are high resistance, unidirectional, agent-specific, variable bypass vaporizers designed to be used outside the breathing system.

Draw-over vaporizers are low resistance and inefficient compared with their plenum counterpart. They are, however, robust, portable, and well adapted to 'field anaesthesia'.

The TEC-6 vaporizer is specially designed to take into account the unique physical properties of desflurane.

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The safe delivery of volatile anaesthesia today is due in part to the development of increasingly advanced vaporizers. Current equipment has evolved from earlier examples which were uncalibrated, and whose output varied greatly with ambient temperature and gas flow rates. The aims of this article are:

(i) to outline the physical properties of vapours and gases and how this relates to the delivery of volatile anaesthesia;
(ii) to classify and describe the vaporizers in common use today.

An understanding of some basic physical properties is essential when discussing vaporizers.

Physical definitions

Vapours and gases

Every substance has its unique critical temperature above which it exists only as a gas, irrespective of how much pressure is applied to it. At or below this critical temperature, it can exist in both its liquid and gaseous forms; the latter is called a vapour.

Saturated vapour pressure

In any liquid, some molecules will have sufficient energy to leave the liquid, becoming a vapour—this is called evaporation. It occurs only at the surface of the liquid and requires heat energy, known as the latent heat of vaporization and will be increased by:

(i) increasing the temperature of the liquid;
(ii) increasing the surface area of the liquid;
(iii) increasing the removal of vapour molecules from the liquid surface.

If the liquid is in a closed container, such as a vaporizer, the vapour molecules collide with the container walls and with the liquid surface, exerting a pressure and potentially being trapped and re-entering the liquid phase. At any given temperature, a point of dynamic equilibrium will come to exist where the number of molecules leaving the liquid phase equals the number re-entering it—at this point, the vapour is saturated and the pressure it exerts is known as the saturated vapour pressure (SVP).

Boiling

As a liquid is heated, its SVP increases in a non-linear fashion (Fig. 1). At a certain temperature, the boiling point, liquid molecules can enter their vapour phase within the liquid, creating bubbles of saturated vapour that rise to the surface and break free. Below this temperature, any formation of a bubble would be instantly crushed by the greater atmospheric pressure.

Thus, boiling occurs at the temperature where SVP equals atmospheric pressure.

The purpose of a vaporizer is to reliably deliver an accurate, adjustable concentration of anaesthetic vapour.

The concentration of the anaesthetic vapour in a gas is given by the equation:

$$\text{Gas concentration} = \frac{\text{Vapour pressure}}{\text{Ambient pressure}}$$

Vapour pressure may vary depending on the factors affecting evaporation discussed earlier; however, at a given temperature, each agent will have a known SVP. If the gas leaves the vaporizing chamber containing agent at its SVP, then a fixed concentration of agent is delivered into the fresh gas flow.

For example, at 20°C, the concentration of gas in a sevoflurane-vaporizing chamber (assuming it is saturated) will be:

$$\text{Sevoflurane conc.} = \frac{21.3}{101.3} = 21\%$$

In order to give clinically useful concentrations of the agent, we dilute this with fresh gas in one of the two ways:

(i) By having an adjustable proportion (the splitting ratio) of gas that either enters or bypasses a vaporizing chamber—variable bypass vaporizers.
(ii) By adding vapour directly to the fresh gas flow—measured flow vaporizers.

doi:10.1093/bjaceaccp/mkr040 Advance Access publication 10 November, 2011

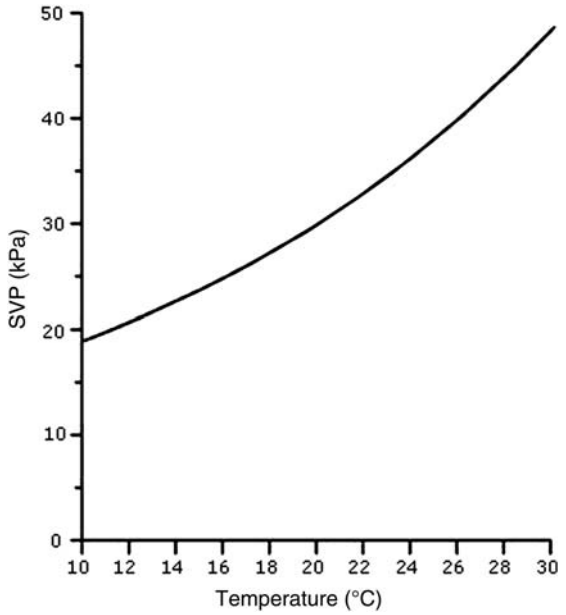

Fig 1 SVP increases non-linearly with temperature. Reproduced with permission of e-Learning Anaesthesia.

Variable bypass vaporizers

Variable bypass vaporizers can be of the plenum or draw-over type. Plenum vaporizers have a much higher internal resistance, requiring fresh gas at above atmospheric pressure. In contrast, draw-over vaporizers use fresh gas flow at atmospheric pressure, driven by the patient's respiratory efforts. This makes them ideal for portable systems such as in the military or where compressed gas is unavailable.

Plenum vaporizers are more accurate,[1] due to design features that largely overcome factors reducing agent vapour pressure in the vaporizing chamber to below their SVP. These factors are described below.

Gas flow rate

As fresh gas flow rate increases, it becomes more difficult to achieve full saturation of gas leaving the vaporizing chamber.[2]

To overcome this, plenum vaporizers maximize surface area for vaporization using wicks, baffles, cowls, or nebulizers. Teflon wicks or shelves of folded metal allow the liquid agent to spread by capillary action over a much larger surface area. Incoming gas is then directed through the vaporization chamber via channels created by metal baffles.

Modern plenum vaporizers produce an accurate concentration of agent at flow rates between 0.25 and 15 litre min^{-1}.

Although some draw-over vaporizers contain wicks, they are less effective than those in plenum vaporizers as their design must keep resistance to a minimum. In addition, the resistance generated by the flow splitting valve becomes more significant at low flow rates—this results in more gas bypassing the vaporizing chamber. Thus, draw-over vaporizers are less accurate at high or low gas flows.

Temperature

The SVP of an agent (and hence the vaporizer output) decreases non-linearly with decreasing temperature. Changes in agent temperature can occur for two reasons—fluctuations in ambient temperature and loss of the latent heat of vaporization (the latter being exacerbated at high gas flow rates).

These problems can be overcome by:

(i) Temperature stabilization: Construction of the vaporizer using materials with high specific heat capacity and thermal conductivity provides a heat sink, allowing heat to move rapidly between the vaporizing chamber and the atmosphere. Plenum vaporizers are made of dense metals, while the Oxford Miniature Vaporiser (a draw-over vaporizer) uses glycol as a heat sink.

(ii) Temperature compensation. Modern vaporizers are temperature compensated (hence the Tec series). The most commonly used methods are:

  (a) Bimetallic strips: consisting of two metal strips with different coefficients of thermal expansion. As temperature decreases, the strip bends, allowing more fresh gas flow to enter the vaporizing chamber. The Ohmeda Universal Portable Anaesthesia Complete draw-over device (previously used by the US Military) utilizes a bimetallic strip while the Oxford Miniature Vaporiser is not temperature compensated.

  (b) Aneroid bellows: these are connected by a rod to a cone in the orifice of the bypass chamber. A reduction in temperature causes the bellows to contract, resulting in the cone partially obstructing the bypass channel, increasing flow through the vaporizing chamber.

Measured flow vaporizers

In contrast to variable bypass vaporizers that split the fresh gas flow, measured flow vaporizers have a separate, independent stream of vapour carrying gas that is added to the fresh flow.[2] To deliver an accurate agent concentration, the vaporizer must measure, and adjust for, fresh gas flow rate. The most common such vaporizer is the Ohmeda Tec 6, designed specifically for use with desflurane.

Desflurane has two physical properties, making it unsuitable for use with a conventional vaporizer. First, it has a very high SVP (88.5 kPa at 20°C). A conventional vaporizer would require high fresh gas flows to dilute it to within clinically useful concentrations, making it uneconomical.

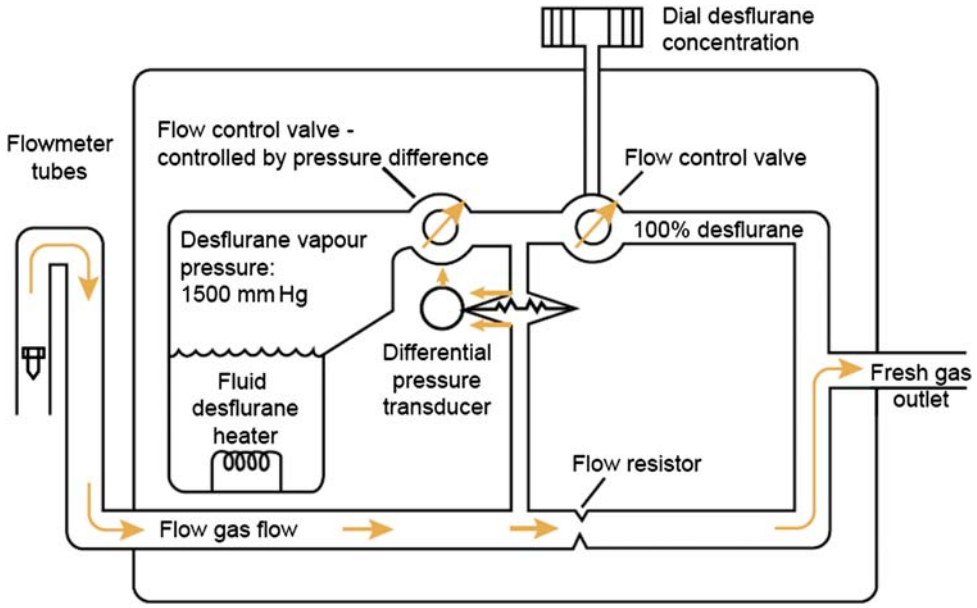

Fig 2 Schematic diagram of the TEC 6 vaporizer. Reprinted with permission of Elsevier.

Secondly, it has a low boiling point (23.5°C). At room temperature, it will intermittently boil resulting in large fluctuations in agent delivery. When boiling, there will be excessive agent delivery; however, it will then cool due to a large loss of latent heat of vaporization, resulting in an exponential decrease in SVP and under-delivery of agent.

The Ohmeda Tec 6 overcomes these problems by using an electrical filament that heats the desflurane to 39°C, raising its SVP to 194 kPa, that is, nearly 2 atm. In addition to providing a stable SVP, this high pressure removes the need for a pressurized carrier gas—instead, the fresh or diluent gas is entirely separate from the vaporizing chamber (Fig. 2).

Gaseous desflurane is added directly to the fresh gas. To provide an accurate agent concentration, the quantity of agent added must be proportional to the fresh gas flow. An automatic adjustment is achieved by a variable resistance at the vaporizing chamber outflow, controlled by a differential pressure transducer. Fresh gas flow passes through a flow resistor, producing a fixed resistance; as flow increases, backpressure against the differential pressure transducer increases—this results in a reduction in the variable resistance, hence increasing vapour output to match the increased gas flow. The reverse occurs as gas flow is reduced.

Finally, the delivered concentration is adjusted manually via the vaporizer dial, linked to a second variable resistance. This dial has an interim stop at 12% requiring depression of the release bar to bypass, allowing the concentration to be increased to 18%.

If the desflurane temperature were to decrease, the vaporizer would fail to deliver accurate concentrations. Solenoid operated locks in the vaporizer dial and at the vaporizing chamber outflow are only released once the operating temperature is reached.

Other factors affecting vaporizer performance

Carrier gas composition

The viscosities of air, and to a greater extent nitrous oxide, are lower than those of oxygen. In the variable bypass vaporizers, the characteristic of the flow splitting valve results in decreased gas flow through the vaporizing chamber, and hence reduced output, when using air and especially nitrous oxide compared with 100% oxygen. The effect is not clinically significant.[2]

With the Tec 6 vaporizer, the reducing viscosities of air and nitrous oxide have the same tendency to lower agent delivery as this reduced viscosity results in less backpressure being generated by the flow restrictor. Again, differences are not great and should have little effect in clinical practice.[3]

Altitude

Although we refer to the MAC of agents in percentages, the clinical effect of volatile agents is determined by their partial pressure in tissues. SVP is unaffected by ambient pressure, therefore the output from the vaporizing chamber is unaffected. The change in the agent concentration in the delivered gas flow can be calculated by:

$$\%^{1} = \%^{\mathrm{cal}} \times \frac{P^{\mathrm{cal}}}{P^{1}}$$

$\%^{1}$, agent %; P^{1}, pressure at a given altitude; $\%^{\mathrm{cal}}$, agent %; P^{cal}, pressure at an altitude where vaporizer calibrated.

For example, if we dialled an isoflurane vaporizer to 2% at atmospheric pressure (where the unit was calibrated):

$$\text{Delivered concentration} = 2\%$$

$$\text{Agents partial pressure} = 2\% \text{ of } 101.3 \text{ kPa} = 2.026 \text{ kPa}$$

If we keep the vaporizer dialled to 2% but reduce atmospheric pressure to 50 kPa:

$$\text{Delivered concentration} = 2 \times \frac{101.3}{50} = 4.052\%$$

$$\text{Agents partial pressure} = 4.052\% \text{ of } 50 \text{ kPa} = 2.026 \text{ kPa}$$

It is important to emphasize that temperature decreases with altitude; this is known as the 'lapse rate' and varies according to the moisture content of the air and has an international standard of 6.49°C per 1000 m from sea level to 11 000 m. This will have a consequence on the SVP, but most modern vaporizers are temperature compensated and most aircraft fuselages are temperature regulated. Thus, the vaporizer can essentially be used in the same way at altitude, sea level, or under hyperbaric conditions.

However, this does not apply to the desflurane Tec 6 vaporizer. The Tec 6 is pressurized to 2 atm; there is no compensation for ambient pressure and thus the concentration delivered in the fresh gas flow is stable, regardless of ambient pressure. If we repeat the above calculations using desflurane at a dial setting of 2%:

$$\text{Delivered conc.} = 2\% \text{ (regardless of ambient pressure)}$$

At sea level:

$$\text{Agents partial pressure} = 2\% \text{ of } 101.3 \text{ kPa} = 2.026 \text{ kPa}$$

While at the reduced ambient pressure of 50 kPa:

$$\text{Agents partial pressure} = 2\% \text{ of } 50 \text{ kPa} = 1 \text{ kPa}$$

Thus, the dial setting must be increased to maintain partial pressure of the agent at altitude (manufacturer's graphs/tables are available to illustrate the required adjustments).

Backpressure

This phenomenon (also known as the pumping affect) occurs when pressure from gas-driven ventilators is transmitted in a retrograde fashion to the back bar and vaporizer.[4] This can force gas in the outflow port back into the vaporizing chamber, leading to two potential problems. First, resaturation of carrier gas (this is only a problem with inefficient vaporizers where gas has not been 100% saturated in the vaporizing chamber during the first pass). Secondly, saturated gas can be forced back through the vaporizer inlet port and enter the bypass channel resulting in increased agent delivery. Techniques to avoid this problem include a one-way valve at the outflow of the vaporizer, ensuring that the vaporizing chamber and bypass chamber are of equal volumes so backpressure is transmitted equally to both or making the vaporizer inflow port long.

The Aladin cassette

Around 10 yr ago, Datex-Ohmeda introduced the Aladin cassette vaporizer specifically for use with their Anaesthesia Delivery Unit. It consists of two parts: the agent-specific vaporizing chamber (the cassette) and the central processing unit (CPU) which is an integral part of the anaesthetic machine. It behaves as both a variable bypass and measured flow vaporizer and tries to overcome some of the problems discussed within this article in the following ways.

Gas flow rate

A throttle valve, controlled by the CPU, regulates the gas flow leaving the vaporizing chamber, with adjustments made for gas flow rate.[5] The fresh gas flow rate is measured using the principle of a pressure decrease proportional to gas flow over a fixed resistance.

Carrier gas saturation is maximized by synthetic lamellae with metal plates that act as a wick.

Temperature

Liquid agent temperature is measured in order to calculate vapour pressure; in addition, total pressure within the cassette is measured to allow calculation of vapour concentration (vapour pressure/total pressure). Based on this, the CPU adjusts the amount of agent added to the bypass gas, thus providing temperature compensation.

Temperature stabilization comes from the metal plates (increasing heat capacity and conductivity) and a fan beneath the cassette which, if agent temperature decreases to <18°C, transfers heat from the workstations electronics to the cassette.[5]

Carrier gas composition

Fresh gas flow selection is fed into the CPU algorithm to try and minimize the effect of different carrier gas viscosities.[5]

Backpressure

Bypass/vaporizing chamber gas flows reunite in a mixing chamber, distinct from the cassette, overcoming the problems induced by ventilator backpressure.

Conclusions

The use of vaporizers is standard practice in anaesthesia today and is likely to continue. The most recent vaporizers have been in use for over a decade and have brought computer-assisted control to maximize accurate agent delivery, particularly at low flow rates. Future developments may occur in conjunction with the discovery of novel volatile anaesthetic agents and there is the possibility of

closed systems, where vaporizer control may be linked directly to patient parameters via feedback mechanisms.

Conflict of interest

None declared.

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Please see multiple choice questions 1–4.