VAPORISERS

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This article should be read in conjunction with Volatile Anaesthetic Agents, Professor Paul Fenton (Update in Anaesthesia 2000; 11: 78-82)

Key to terms

SVP	Saturated vapour pressure
IPPV	Intermittent iositive pressure ventilation
Anaesthetic Circuit	Anaesthetic breathing system
1.0 kPa	7.5 mmHg

DEFINITIONS

Vapours, Gases, and Critical temperature

A vapour is generally defined as a gaseous substance which, at room temperature and pressure, can also exists in liquid form. It condenses back to liquid relatively easily and will also evaporate easily.

The scientific distinction between a vapour and a gas is as follows. For any gaseous substance, there is a maximum temperature, the critical temperature, at which it can be compressed so as to convert it from a gas to a liquid. Once above that critical temperature, however, it cannot become liquid, no matter how much pressure is applied. It is then no longer defined as a vapour, but is defined as a gas. The critical temperature varies for different substances. For instance the critical temperature of nitrous oxide is 36.5^0C. Therefore at room temperature, it is a vapour and when compressed in a cylinder, exists in the liquid and gaseous form. In a few locations in the world where anaesthesia is conducted in temperatures above its critical temperature it behaves as a gas. In contrast, oxygen is a gas in all climates, unless it is cooled below -118^0C, its critical temperature. Therefore liquid oxygen supplies must be kept below this temperature *(Update in Anaesthesia 2000; 12: 6-11)*

What we call 'volatile anaesthetics' are liquid at room temperature and atmospheric pressure. Liquids consist of molecules which are in constant motion and have a mutual attraction to each other. If the surface of the liquid is exposed to air, or any other gas, some molecules will escape from the surface when their energy is more than the energy of the attraction to the other molecules. This is the process of evaporation which is increased with heating. Volatile agents are able to evaporate easily and do not require heating to liberate the vapour. If we pour a volatile agent into a confined space, such as a jar with a lid on it, over time the vapour liberated from the liquid accumulates in the space available in the jar. As it accumulates the molecules move randomly and exert a pressure. In the enclosed jar some of the molecules that have escaped will collide with the surface of the liquid and re-enter. Ultimately the process reaches equilibrium. At that point there are equal numbers of molecules leaving and returning to the liquid. The "saturated vapour pressure" (SVP) is the pressure exerted by the molecules in the vapour at the point of equilibrium. If the liquid is not contained in a confined space the process of evaporation continues until all of the agent has converted from liquid to vapour and dissipated into the surrounding atmosphere. Leave the lid off a bottle of halothane and there won't be any left an hour or two later!

Table 1: Boiling points and SVP of commonly available volatile anaesthetics

Agent	Boiling point (celcius, 1atm)	Saturated vapour pressure (mmHg, 20°C)	Latent heat of vaporisation (kJ/mol)
Halothane	50.2	241	28.9
Ether	34.6	442	27.6
Enflurane	56.5	175	32.3
Isoflurane	48.5	240	-
Trichloroethylene	86.7	58	31.3
Methoxyflurane	104.7	22.5	33.9
Sevoflurane	58.5	160	-

Information collated from "Clinical Anaesthetic Pharmacology" Ed JW Dundee, RSJ Clarke, W McCaughey. Churchill Livingstone 1991.

Saturated Vapour Pressure (SVP)

As explained above, the SVP is defined as the pressure exerted by the vapour in equilibrium with the liquid phase. It is dependent on the agent concerned, and its temperature, nothing else. When SVP is equal to atmospheric pressure, the liquid boils, i.e pure water at sea level at 100°C has an SVP = 760mmHg (101.3kPa).

Latent heat of vaporisation

Energy is needed to convert a substance from a liquid state into vapour or gas. The latent heat of vaporisation is defined as the amount of energy required to convert 1g of liquid into vapour without a change in temperature. The more volatile the liquid is, the less energy required. The latent heat of vaporisation is expressed as kJ/g, or kJ/mol, considering different agents have different molecular weights. If the energy is not supplied from an external source then it must be taken from within the liquid itself. This causes the liquid to cool (heat energy is used). Drop some halothane or ether on your forearm and feel it cool as it evaporates, taking heat from your skin.

Volatility

This is the common term which links latent heat of vaporisation and saturated vapour pressure. The more 'volatile' an agent, the less energy required to convert liquid into vapour, and the more pressure exerted by that vapour at a given temperature. It is agent and temperature dependent. Trichloroethylene, for instance, is less volatile than ether.

Examples of points made so far:

Take the lid off a tin of paint and you will smell its vapour. The smell is strong at first, because the vapour is concentrated in the tin. It is in equilibrium with the paint. We say it is 'saturated'. The tin has been closed for a long time, and the saturated vapour pressure is the point where equal numbers of paint molecules are becoming vapour, or returning into the liquid (paint). Very soon after removing the lid the smell disappears. The vapour has diffused away in the atmosphere, and because the paint is poorly volatile, very little is liberated from the paint. If left open, the paint becomes solid before it evaporates.

Compare this with petrol, which is more volatile. If the lid is left off the tin the smell continues to be strong as large amounts of vapour are being released from the petrol. Within a short time there is no petrol left in the tin, it has all become vapour and dispersed into the atmosphere. If the petrol can was filled on a mild day, on a hotter day the tin will hiss out as you open the lid, and on a colder day the tin sucks air in. The SVP is higher on hot days, and lower on cold days, because it is dependent on temperature.

VAPORISERS

Vaporisers are devices designed to deliver safe concentrations of volatile anaesthetic vapour to patients' breathing circuits. The volatile agent goes in to the vaporiser in liquid form, and amazingly comes out as a vapour, at precisely the concentration desired by the anaesthetist! There are features common to most vaporisers, such as the variable bypass channel, and the vaporising chamber, but most vaporisers are agent specific, meaning their dimensions are based on the characteristics of one volatile agent, and they only perform reliably if used with that agent.

VAPORISER CLASSIFICATION SYSTEMS

Most classification systems are academic or cumbersome, and have reducing clinical relevance the more comprehensive they become. In practical terms it is important to be able to discriminate between different characteristics that dictate how they are used, or how they may be expected to perform. Develop your own system. In terms of practicalities, the following distinctions can be made:

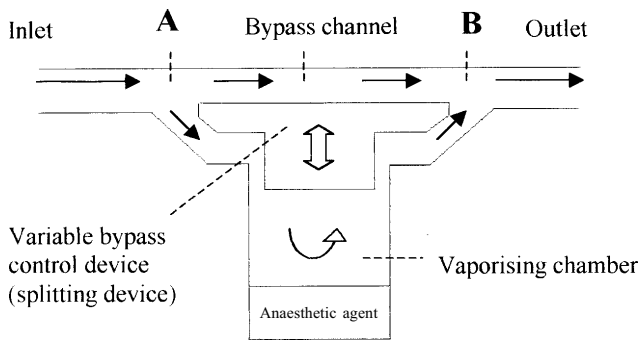

Figure 1: Basic elements of a vaporiser.
Carrier gas enters the inlet. At point A the gas is split into 2 streams, one passing along the bypass channel, the other directed into the vaporising chamber. Amount of flow into the vaporising chamber is controlled by the "splitting device". In the vaporising chamber the gas is saturated with anaesthetic vapour. At point B vapour mixes with the bypass gas, and then exits via the outlet.

- **Drawover v plenum.** Drawover is when carrier gas is pulled through the vaporiser by a decrease in downstream pressure, and plenum is when carrier gas is pushed through the vaporiser at higher than ambient pressure.
- **Agent specific v multi-agent.** Determines what agent can be used in them, or should go in them!
- **Temperature compensated?** Indicates a consistency of performance with time, over a range of operating temperatures, versus a need to adjust dial settings according to decreasing output as vapour cools as it evaporates
- **Flow stabilised?** At what flow rates will the output be reliable?
- **Flow resistance?** How much effort is required to draw, or push, carrier gas through the vaporiser?

Combining some of the above characteristics vaporisers can broadly be classified into 2 main categories, as follows

1. Drawover or Plenum
2. Calibrated or Uncalibrated

Calibration is the term used to describe the precision of performance within a specified range of conditions. Manufacturers can supply data to show how well output matches ideal performance. Giving a hypothetical example a vaporiser may be calibrated to perform within ± 10% of the dial setting, at flow rates between 2

and 10 litres per minute. Outside these limits the performance is less reliable. The structural methods used to improve calibration are those outlined below.

VAPORISER STRUCTURE

The basic components are the vapour chamber and the flow-splitting device. In all situations other than open-drop anaesthesia the vapour needs to be delivered to the patient in a carrier gas passing along a circuit. Volatile agents cannot just be poured in because their SVP is too high, and the final concentration would be too great, causing overdose. The vaporiser is used to add a safe, predictable and controlled concentration, a small percentage, into the anaesthetic circuit.

Most vaporisers use the method of "splitting" the carrier gas into two streams as it passes through. One stream passes into the vaporising chamber, and the other passes by (by-passes) directly into the anaesthetic circuit without contacting the vapour. The ratio of the gas flows in each stream is called the "splitting ratio". The splitting ratio is principally controlled by the concentration dial, allowing the anaesthetist to vary the output according to the desired amount.

The exception to all of the above is the "copper kettle" which is a 'measured flow' vaporiser, as opposed to 'variable bypass'. It will not be considered further, here.

Downstream of the vaporiser the streams of vapour-laden, and vapour-free gas mix in the anaesthetic circuit. In calibrating the vaporiser, the manufacturer assumes that all carrier gas passing through the vaporising chamber becomes saturated with anaesthetic vapour, which has a known concentration. The desired output can then be produced by altering the splitting ratio which alters the dilution of the vapour laden gas with fresh gas to give a final concentration in the clinical range. It is vital therefore that the vaporising chamber produces a saturated vapour. This is achieved by the following devices.

- Wicks are used to increase surface area of the liquid/gas interface where vaporisation is occurring, ensuring saturation of carrier gas as it passes through. This is crucial to the determination of output. Without wicks the vapour concentration will not achieve SVP, because too little vapour can be liberated from the small interface in unit time as the carrier gas passes through (taking vapour away). Performance will fall with time. One example of a wick-less vaporiser is the Goldman.

- Baffles are simple plates or channels that encouraging mixing of carrier gas with vapour, ensuring saturation before the carrier gas returns to the anaesthetic circuit.

- Temperature compensation devices. Since SVP is dependent on temperature, the output of the vaporiser will be different at different temperatures if the splitting ratio remains fixed. As temperature falls the SVP falls, so the concentration leaving the vaporising chamber will fall and thus contribute less vapour to the carrier gas as it passes through, and the final output (%) will fall, unless the splitting ratio alters to accommodate the change. This is exactly what the manufacturers have introduced, and called "temperature compensation". There are various designs which achieve this, but the common element is an indirect increase in the splitting ratio with a fall in temperature, without any alteration of the dial setting, by outflow modification. (see below)

The aim of the calibrated vaporiser is the provision of a steady, predictable output that correlates with the dial setting in a wide range of environmental conditions.

To offset the cooling effect of vaporisation (latent heat) vaporisers are built from conductive materials which can donate heat energy to the liquid. A large mass of such material is referred to as a "heat sink". Examples include the water bath of the EMO, and the thick copper base of the Tec vaporisers. Improvised heat-sinks can be made, such as wrapping a warm, wet towel around a Boyle's bottle when using ether.

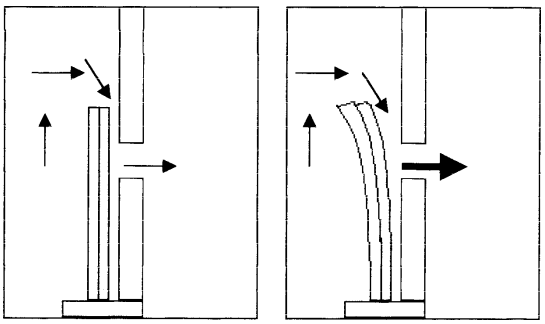

Figure 2a. Bimetallic strips
The two metals expand or contract in response to temperature, but at different rates such that the strip is forced to bend away from the aperture when the system cools, allowing more vapour out, and compensating for the decrease in vaporisation at the lower temperature.

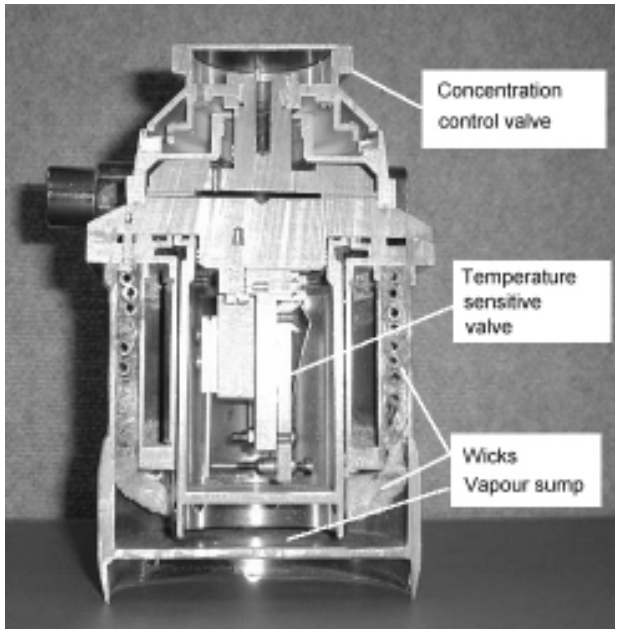

Figure 2b: Cut-away view of a Fluotec2 halothane vaporiser (Cyprane, UK) Note the solid metal structure which acts as a heat sink and the wicks to aid vaporisation. Note the complex internal construction of the temperature compensation valve which causes high internal resistance in contrast to the EMO (figure 3a). This vaporiser cannot be used in a drawover mode.

Further temperature compensation (flow compensation) occurs by internal adjustments in the splitting ratio when temperature falls or rises. The commonest method for achieving this is with a bimetallic strip (Tec series) in which two conjoined, dissimilar metals expand or contract at different rates as temperature varies, thus opening or closing the output aperture of the vapour chamber. An alternative system is the ether-filled-bellows (Penlon) attached to a spindle valve. The bellows change size with temperature changes, altering the relationship of the spindle to the seat, with an effect on the output, and therefore the splitting ratio. As vapour cools the bellows shrink, and the aperture increases, allowing a greater 'output'.

DRAWOVER VAPORISERS

The distinction between operational needs of draw-over and plenum anaesthesia will be covered in a subsequent article.

The basic elements are:

- Low internal resistance to gas flow
- Gas is drawn through the vaporiser into the anaesthetic circuit only in inspiration, or by the use of a self inflating bag or bellows, therefore flow is not constant (peak inspiratory flow rates 30-60l/min), but 'pulsatile'.
- Do not require a pressurised gas supply

Goldman halothane vaporiser (similar to McKesson and Rowbotham -Trilene) Adapted from Leyland fuel pump. Very simple splitting device. No temperature compensation - therefore output varies with temperature, and decreases during use as the temperature falls. With halothane the maximum output is 3% because of the small vapour chamber and absence of wicks. It can be used in a circle system, but needs vigilance as the output varies dramatically depending on whether the patient is spontaneously breathing (lower), or ventilated by positive pressure (higher). Circle flow rates also influence output. This area is too complex to tackle within this broad article.

Figure 3a: The EMO ether vaporiser. Note the mass of water providing the heat sink, and the temperature compensation device - an ether filled bellows

Oxford Miniature Vaporiser (OMV) (drawover or plenum).

- Portable
- Multi-agent
- Easliy cleaned and serviced
- Wire-gauze wick
- No temperature compensation
- Small heat sink containing glycol

EMO ether inhaler (Epstein, Macintosh, Oxford)

- Robust
- Water-bath heat sink
- Ether bellows temperature compensator
- Level indicator

Open drop techniques (ether and chloroform) - e.g. Schimmelbusch mask and Ogston's inhaler

- Drop rate gives inspired concentration
- Number of layers of gauze or lint important (wick)
- Freezing may occur (latent heat)
- Eye protection needs to be considered (freezing)

PLENUM VAPORISERS

Plenum is a term derived from Latin, and means "full". It is the opposite to vacuum. In air conditioning terminology it applies to air that is forced in, cleaned and temperature adjusted. Plenum vaporisers are designed for use with continuous flow of pressurised gas, and have high internal resistance. Modern versions are universally agent specific, and referred to as "flow stabilised"; ie. perform equally well over a large range of fresh gas flow (FGF) (±20% accurate 0.5-10 l/min).

Boyle's bottle. Not temperature compensated, nor agent specific although designed for use with ether. The cowling over the U-tube forces gas to bubble through ether when down, increasing output by increasing the gas/liquid interface. There is the potential for a surge of high concentration of ether when first turned on, as the chamber contains ether at SVP (equilibrated while standing idle SVP is 60kPa - (60/101.3) x 100 = 59.2% or 450 mmHg - (450/760) x 100 = 59.2%). Cools dramatically in use with a drastic decrease

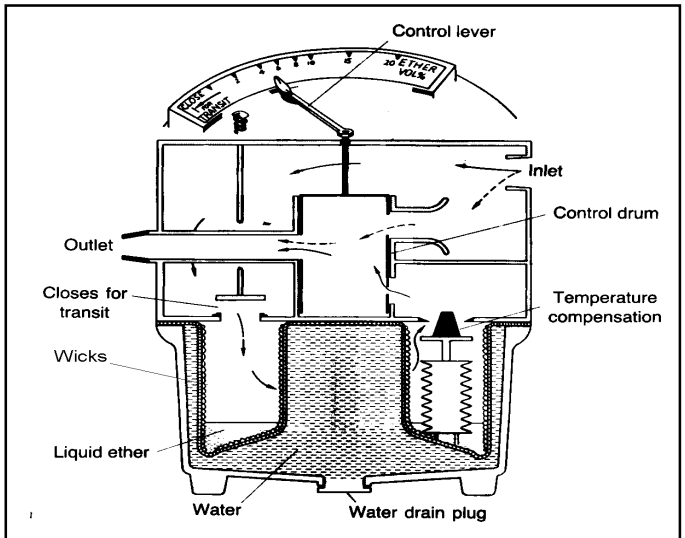

Figure 3b: EMO ether vaporiser, Oxford inflating bellows and breathing system

in output, and the possibility of the patient lightening or awakening unless counteracted by an external heat sink (hot towel, or warm water bath) and further depression of the cowling into the ether liquid. May need frequent refilling while in use,.

Tec 2 (Ohmeda) Halothane vaporiser

- Temperature compensated
- Bimetallic strip
- Series of wicks
- Metal heat sink

Many newer models of vaporisers exist and have refined performances, particularly for low flow rates to facilitate low flow circle anaesthesia. They are characterised by larger wicks, output resistance to minimise the 'pumping effect' and metal heat sinks

PUMPING EFFECT (INCREASED VAPOUR OUTPUT AT LOW FLOWS)

This effect applies to plenum vaporisers especially at low flow rates with IPPV when back pressure is exerted on the vaporiser. Typically this happens when manually assisted or ventilator controlled ventilation is being used.

The pressure in the anaesthetic circuit and vapour chamber rises during inspiration. This drives some saturated vapour back from the vapour chamber into the inlet path, which spills into the bypass carrier gas when the pressure falls during expiration. The by-pass is thus contaminated and will result in an inaccurate output concentration. Designers have minimized the effect by increasing the internal resistance which reduces the back flow into the vaporising chamber. Other measures to prevent it include an outlet 'non-return valve' (resistance) which maintains constant pressure in the vapour chamber, and long high-resistance inlet pathways. (Drager)

PRESSURE EFFECT (DECREASED VAPOUR OUTPUT AT HIGH FLOWS)

Applies to plenum vaporisers at high flow rates during IPPV and is of minor significance. Positive pressure compresses the carrier gas, thus concentrating it. When the pressure is released (expiration), volume increases, the gas density falls and the vapour concentration also falls.

VAPORISER SAFETY

To enhance the safety aspects of using volatile agents the following adaptations have become commonplace:

- Keyed filling devices reducing the likelihood of filling with the wrong agent
- Agent level indicators
- Stable mounting brackets to prevent tipping and spillage
- Correct placement in circuit:
- Plenum Downstream from rotameters, upstream of oxygen
- Draw-over Upstream from self inflating bag/bellows
- Interlock devices to stop the concurrent use of two vaporisers in series, preventing contamination from upstream to downstream vaporiser. If an interlock device is fitted, a small metal rod protrudes from the side of the vaporiser, towards the rear. When the dial is turned on, the rod sticks out further. If two interlock compatible vaporisers are mounted side by side then this prevents the second vaporiser from being switched on as the rods are in contact, and the second dial will not turn.
- Correct placement in series (if no interlock): More volatile agents (highest SVP) placed downstream as less volatile agents have lower splitting ratios and will create less contamination of downstream vaporisers if both are switched on. Halothane downstream to prevent thymol contamination of others
- Agent monitoring, checking that the circuit concentrations are adequate

Potential misadventures

- Overfilling may have an unpredictable effect on output. Liquid agent may spill into the bypass and increase output dramatically, or conversely, reduced wick surface area may lead to reduced output. If overfilled it is wise to drain the vaporiser to the recommended range as indicated by the agent indicator.

- Crossed connection-reversed connection. Will lead to unpredictable output. In the Tec series the manufacturers claim this to be approximately double what is dialled. Not recommended!

- Tipped over. High output as the splitting device inlet is contaminated by liquid agent and bypass gas also collects vapour. Needs to be flushed for 10 mins at 10 litres/min before use, or left to stand overnight.

- Incorrect filling (wrong agent). Output will not match dial setting, and may be grossly excessive (overdose), or inadequate (intraoperative awareness) if used by an unsuspecting anaesthetist

Hypobaric and Hyperbaric environments

In these situations the output from the vaporiser can alter. SVP remains unchanged as it is only temperature dependent, but there is a change in ambient pressure relative to SVP. This then alters the output concentration (%). However the partial pressure of the vapour does not change. Since the partial pressure of the volatile agent is the important factor in causing anaesthesia, there is no reason to vary the vaporiser settings from normobaric use. If using agent monitoring, however, the MAC value in % will be inappropriate and should not be relied upon. Use mmHg or kPa as a guide instead. Pressure reversal of anaesthesia is not a clinically significant phenomenon in commonly used therapeutic hyperbaric chamber pressures.

Final words

It is impossible to cover all aspects of vaporiser function and performance, in all conditions, with all agents. Hopefully an understanding of the general principles involved will allow you to predict what is safe, unsafe, achievable, or impossible when confronted with clinical choices, or a need to modify the use of a vaporiser to suit your own particular needs.