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Vaporisers

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Summary

This article should be read in conjunction with the previous article, 'Gases and vapours'. Several areas and concepts are duplicated but are retained for the benefit of an alternative explanation. Full coverage of the features of all vaporisers is clearly not possible, however the common underlying principles of their function are demonstrated using examples of widely-used devices. A clear understanding of the uses and pitfalls of vaporisers is essential for their safe clinical use.

DEFINITIONS

Definitions of the terms vapour, gas, and critical temperature can be found in the previous article, *Gases and vapours.*

'Volatile anaesthetic agents' 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 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 the liquid phase. 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!

Saturated vapour pressure

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 of 101.3kPa (760mmHg, one atmosphere).

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 $kJ.g^{-1}$, or $kJ.mol^{-1}$, considering that different agents have different

Table 1. *Boiling points and SVPs of commonly available volatile anaesthetics*

Agent	Boiling point (°C, at one atmosphere)	Saturated vapour pressure at 20°C (mmHg)	(kPa)	Latent heat of vaporisation ($kJ.mol^{-1}$)
Halothane	50.2	241	32.3	28.9
Ether	34.6	442	58.2	27.6
Enflurane	56.5	175	23.3	32.3
Isoflurane	48.5	240	33.2	-
Trichloroethylene	86.7	58	7.6	31
Methoxyflurane	104.7	22.5	3.0	33.9
Sevoflurane	58.5	60	22.7	-
Desflurane	23.5	678	89.2	-

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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. This is also the rationale behind using ethyl chloride to 'freeze' the skin as a topical anaesthetic.

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 a patient's breathing circuit. The volatile agent goes into the vaporiser in liquid form, and 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.

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:

Drawover versus 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 versus multi-agent

Determines what agent can be used 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?

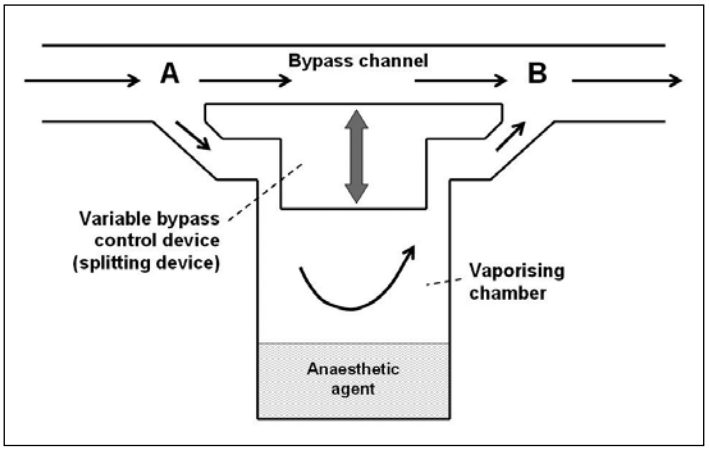

Figure 1. *Basic elements of a vaporiser. The carrier gas enters the inlet. At point A the gas is split into two streams, one passing along the bypass channel, the other directed into the vaporising chamber. The amount of flow into the vaporising chamber is controlled by the 'splitting device'. In the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

Combining some of the above characteristics, vaporisers can broadly be classified into two 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 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 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, and 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 from 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 determines the dilution of the vapour-laden gas with fresh gas to give a final concentration in the desired 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 the surface area of the liquid/gas interface where vaporisation occurs, ensuring saturation of the carrier gas as it passes through (see Figure 2). 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.

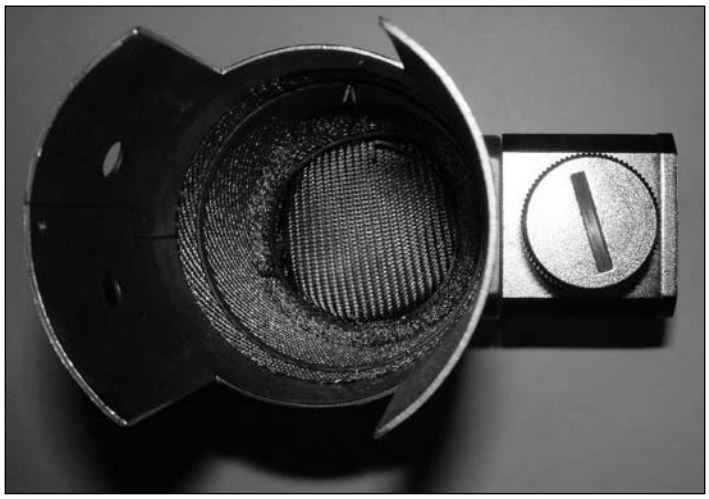

Figure 2. *The wick system of an Oxford miniature vaporiser (OMV) consists of metallic mesh*

- **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 device**s. 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 it is termed 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 Figure 3).

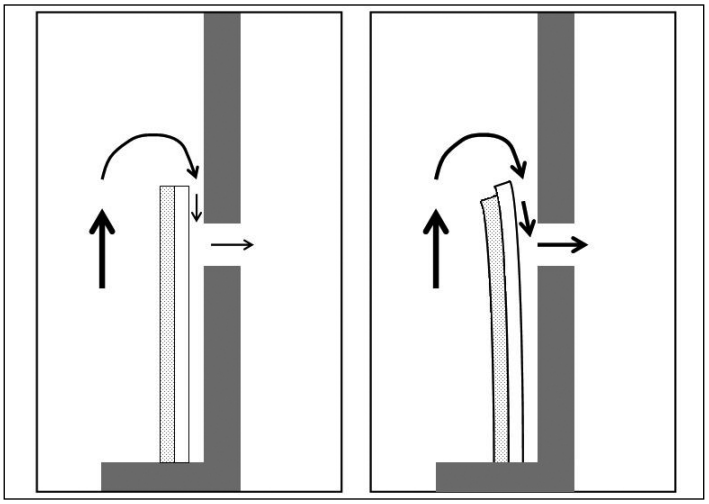

Figure 3. *Bimetallic strips. The two metals expand or contract in response to temperature, but at different rates such that the strip is forced to bend away from the aperture when the system cools, allowing more vapour out, and compensating for the decrease in vaporisation at the lower temperature*

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. 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 (Figure 3), 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 (Figure 6). 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 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^{-1}), but more 'pulsatile' in nature.

- 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.

Oxford Miniature Vaporiser (OMV) - drawover or plenum (Figure 5)

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

Figure 5. *The Oxford miniature vaporiser (OMV)*

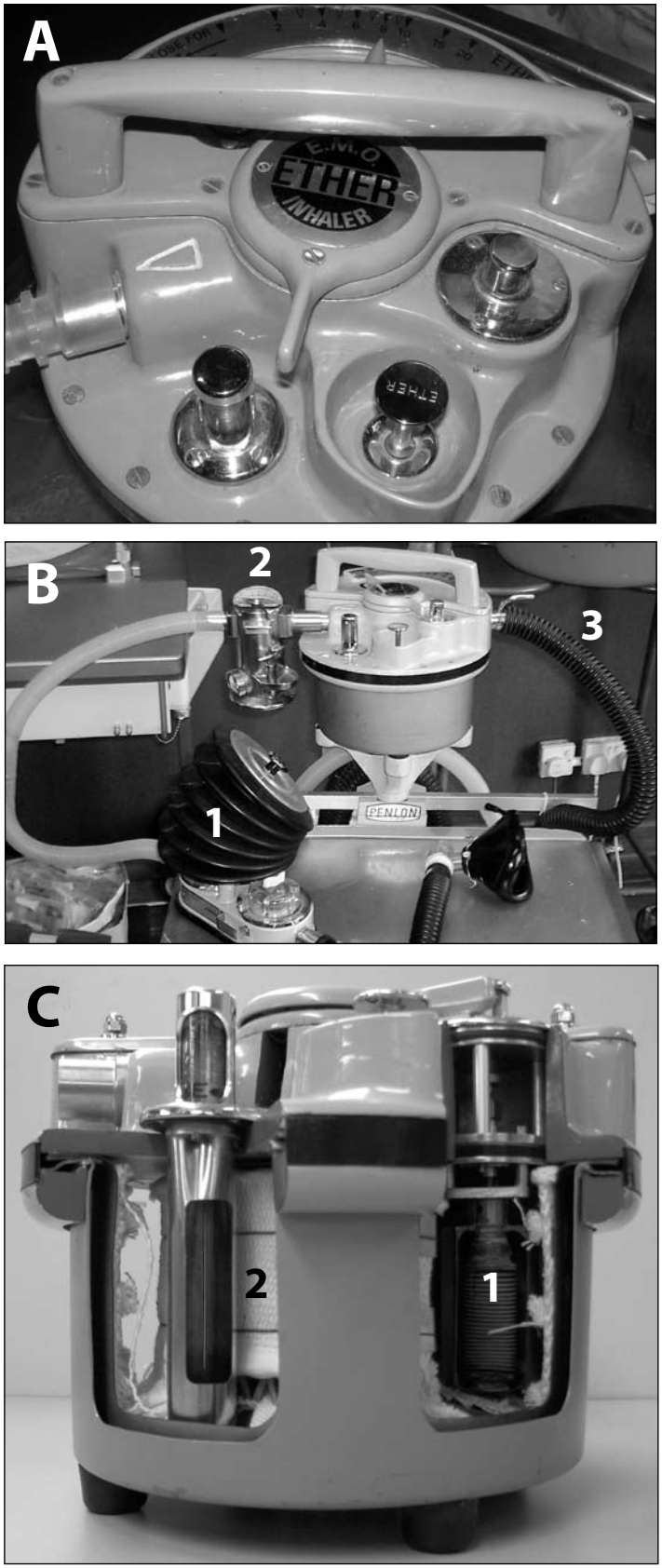

Figure 6. *(A) The EMO ether vaporiser, (B) EMO in a drawover circuit with Oxford inflating bellows (1), an OMV in series (2) and a patient breathing system (3), (C) Cut-away EMO showing temperature compensating bellows (1) and wick system (2)*

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 ('empty'). 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, i.e. they perform equally well over a large range of fresh gas flows, usually ±20% accurate between 0.5-10l.min^{-1}.

Boyle's bottle

This vaporiser is neither temperature compensated nor agent specific, although designed for use with ether. When in the down position, the cowling over the U-tube forces gas to bubble through ether, 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. While standing idle the equilibrated SVP of ether is 60kPa - this constitutes a concentration of 59.2% ([60/101.3] x 100).

The vaporiser cools dramatically in use, with a drastic decrease in output with 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. They tend to 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 by-pass 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)

This effect is seen in 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); the more volatile agents (highest SVP) should be placed downstream, as less volatile agents have lower splitting ratios and will create less contamination of downstream vaporisers if both are switched on. Halothane should be placed downstream to prevent thymol contamination of others vaporisers.
- 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**. This will lead to unpredictable output. In the Tec series the manufacturers claim delivered concentration to be approximately double that dialled.
- **Tipping over** results in high output as the splitting device inlet is contaminated by liquid agent and bypass gas also collects vapour. The vaporiser should be flushed for 10 minutes at 10l.min^{-1} 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 kPa or mmHg as a guide to the partial pressure instead. Pressure reversal of anaesthesia is not a clinically significant phenomenon in therapeutic hyperbaric chamber pressures.

CONCLUSION

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.