CONSIDERATIONS IN THE DESIGN AND FUNCTION OF ANESTHETIC VAPORIZERS

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Vaporized liquid anesthetic agents still have an important place in clinical anesthesia, either singly or as adjuvants to some other agent such as nitrous oxide. It is therefore important to understand the principles which govern the facility with which they can be effectively used. For most satisfactory use, a predictable, reproducible concentration of vapor must be available for introduction to the patient or anesthesia system under circumstances which allow actual vernier control of the concentration according to the needs of the moment. In order to achieve this, efficient vaporization, accurate means of metering concentration, and a high degree of thermostability will be required. All devices which have been used for vaporization have compromised to some extent with one or more of these desiderata and have therefore fallen short of the ideal.

Performance depends upon the original principles incorporated in the design. Any apparatus must be used in accordance with design and in full awareness of the limitations dependent upon the deficiencies in that design. It is not possible to get completely satisfactory performance out of an apparatus in which important principles have been overlooked and, correspondingly, deficient apparatus which can be used safely with one agent may be highly dangerous with a more potent agent which has different vaporization characteristics.

Factors Influencing Effectiveness of Vaporization

The concentration of a vapor produced is a function of both the temperature of the liquid being vaporized, and the product of the total surface and time of contact at the gas-liquid interface. The energy required for vaporization of a liquid must be supplied in accordance with its latent heat of vaporization. If this energy is not provided from an external source, the temperature of the liquid will fall and the tension of the vapor above the liquid will be reduced in proportion to the vapor pressure curve of the particular liquid. Therefore in the design of effective apparatus, it is important to provide for the conduction of heat directly to the gas-liquid interface. If the surface of the gas-liquid interface is small, the gas which passes through the vaporizer must remain in contact with the liquid for a prolonged time

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in order to approach saturation with the vapor, at the particular temperature of that liquid. Conversely, if the surface is sufficiently large the time of contact becomes relatively unimportant.

Historical Development

The majority of vaporizers which have been used during the past one hundred and twelve years, have neglected or ignored one or more of the important factors of effective design. As a result many inefficient and worrisome pieces of apparatus have been used by generations of anesthetists. Common faults have been, the lack of provision for a continuous heat supply, inadequate conduction of that heat to the gas-liquid interface, and insufficient contact of the gas with the liquid. Also, not infrequently the control of the ultimate concentration of the vapor offered to the patient has been dismally poor. None the less there were many ingenious solutions to the problem of vaporization, some of which are worth reviewing and examining.

Morton's original apparatus was a glass bottle containing a sponge to provide a large surface for the gas-liquid interface. A later model incorporated a reservoir and mechanism through which additional ether could be dropped upon the sponge. Other designers followed his lead and we have had in use until today various adaptations of a dropper bottle, from which drops fall upon a surface, such as a mask or a wire screen, through which passes the gas which is offered to a patient. In some of these heat is actually provided to the screen from other parts of the apparatus, such as from the absorber or from a water jacket.

John Snow, in designing two very excellent vaporizers for his time, kept well in mind some of the cardinal principles necessary for effective vaporization. His chloroform vaporizer provided additional surface by the use of "bibulous paper" or blotting paper which by capillary attraction increased the gas-liquid interface. More recent adaptations of this are familiar to all of us in the wick type of bottle. John Snow made use of another principle in his ether vaporizer wherein he caused air to pass over a long distance of liquid ether through a maze, thereby increasing both surface and time-of-contact relationships to increase the efficiency of vaporization. Snow in his original devices, used copper which has a high heat capacity and a rapid conductivity. Several other designers after Snow, used vaporizer systems in which there were baffles which increased the contact time of the air or gases passed over the liquid to be vaporized.

The most practical way of achieving a saturated vapor is the provision of a large surface for the gas-liquid interface by bubbling the gas through the liquid. The sum of the surface areas of the individual bubbles is of considerably greater magnitude than the surface which can be provided by any maze, baffle, or wick arrangement. The more finely divided the gas flow, that is the smaller and more multitudinous the bubbles, the greater will be the total surface provided by this dispersement. The Junker's inhaler was the first device in general use in which an attempt was made to increase the gas-liquid interface by bubbling gas through a liquid. It was a forerunner of gases under pressure, since it supplied carrier gas by means of a hand bellows operated by the administrator according to the need of the moment. The Boyle's bottle is an example of a more modern bubble bottle designed for use with gases under pressure. In vaporizers of the Boyle's type it is possible to pass all the gases past the bottle without coming in contact with the liquid to be vaporized, or to allow a portion or all of this carrier gas to pass over the surface of the liquid, or it is possible to allow a portion or all of the gases to pass through a liquid. Unfortunately most bubble bottles have been designed so that only very large coarse bubbles are produced which do not sufficiently increase the surface time relationships to provide saturated vapor at the working temperature. In addition most bubble bottles have been made of glass which is notoriously poor as a conductor of heat so that there is a rapid decrease of temperature in the liquid and a correspondingly sharp reduction in the concentration of vapor above the liquid in accordance with the vapor pressure of that particular liquid.

An inhaler devised by Joseph Clover supplied heat through a water jacket and a metal container which conducted heat from the anesthetist's hands to the vaporizing surface. This was a rebreathing device which allowed further increase in the concentration of ether by the increased time of contact, but it was defective in that the concomitant accumulation of carbon dioxide was ignored. In this and a number of other vaporizers of the same era, the anesthesia provided appears to have been a combination of hypoxia, hypercarbia and ether.

Many of the vaporizers previously discussed depended upon the respiratory activity of the patient to "draw over" or pass gases over the liquid to be vaporized. This is a useful principle which has not been completely abandoned even today. Modern apparatus which has been designed under this principle includes the Oxford vaporizer 1, several Trilene inhalers, and more recently the E.M.O. inhalers for ether and halothane.

With the advent of gases under pressure it has become possible to modify vaporizing equipment advantageously. These advantages were not immediately perceived or utilized by the designers of vaporizers. Vaporizers continue to be designed so that of the total flow of gases offered to the patient a variable portion is diverted across the liquid to be vaporized. In such systems increments in concentration are likely to be sudden, gross and irritating. These undesirable features contribute to the difficulty in providing smooth anesthesia. Some vaporizers, such as those used in the circle system, still depend upon the patient pushing and pulling gases across or through the vaporizer.

Since provision of a potent and predictable concentration are among the major considerations in an ideal vaporizer, it may be well to look briefly at three other vaporizers which have been designed over the years. The first of these is the well-known Oxford vaporizer 1, which makes use of the latent heat of crystallization of the hydrate of calcium chloride. If the calcium chloride is melted by the addition of heat, through the hot water jacket, it will in turn give up its heat to a colder substance, in this instance the ether, keeping it at an even temperature during the entire period of recrystallization. This has the obvious advantage of providing a fixed concentration of ether vapor to the patient for any one setting on the control tap.

The other two vaporizers deliver ether vapor in a concentration of 100 per cent. The vapor from these must be greatly diluted with air or other gases to prevent overdosage, since the concentrations they deliver are lethal. The first of these is the Pinson Bomb. Liquid ether in a stout metal container is maintained at a temperature well above its boiling point by immersion of the whole container in hot water. The pressure of ether vapor within the container then exceeds atmospheric pressure, so that when the needle valve is open undiluted ether vapor is released. The vapor is then led through a narrow rubber tube to an open mask where it is freely diluted with air. The disadvantage of this and the lack of safety to the patient are obvious. The second such device is known as the Oxford vaporizer 2, in which liquid ether is also maintained at a temperature well above its boiling point. This provides a situation analogous to a cylinder of nitrous oxide in which vapor escapes freely as soon as the valve is opened. The flow rate of this undiluted vapor is measured by a rotameter in the same way as the flow of other anesthetic gases except that it is necessary to keep the rotameter warm to avoid condensation within it. From this ether meter the vapor is led to a warm mixing chamber in which it is admixed with oxygen and other gases. This has disadvantages similar to that of the Pinson Bomb with lethal consequences if there is failure of the diluting gas flow.

The two Oxford vaporizers described above have what might be termed chemical thermostats. A number of other devices have been designed with the prime consideration of maintaining thermostability. The E.S.O. Inhaler for chloroform, which was intended for use of airborne troops during World War II, had some degree of thermocompensation by means of a manually controlled variable orifice which could be set in accordance with a temperature scale reading. Automatic thermocompensators were built in to some of the inhalers for use with Trilene, the E.M.O. inhalers for ether and halothane, and in the recently devised Fluotec. The Oxford vaporizer 1, the E.S.O. and the E.M.O. vaporizers were designed as "draw over" apparatus which depend upon the patient's own respiratory effort, and therefore the ultimate concentration to the patient is somewhat altered dependent upon the characteristics of the respiration and the total flow produced by the respiratory minute volume.

Apparatus incorporating the "draw over" principle has, in its portability, some logistic advantage during war time. However, because of the space taken up by the vapor in a vapor-air mixture, the partial pressure of oxygen provided to the patient in such a system is lower than 20 per cent unless some provision is made to enrich it.

Design of the Copper Kettle

The vaporizer which is now familiarly known as the Copper Kettle was actually designed for chloroform. (1). The prime consideration in seeking a better vaporizer for chloroform was to obtain vernier control over the concentration of such a potent vapor. It became obvious that it would be necessary to depart from the traditonal system of diverting a portion of the total flow of gases over the liquid to be vaporized and instead utilize advantages which could be obtained by metering a known amount of gas flowing through the vaporizer in variable pro-

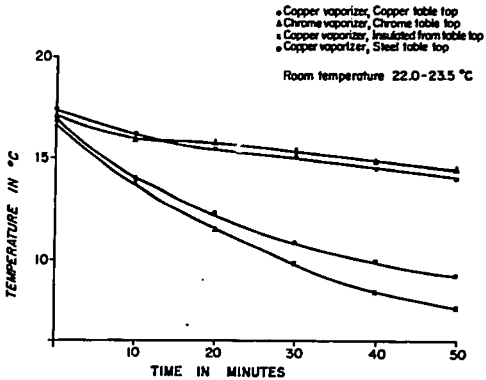

Fig. 1. Thermostability of Copper Kettle when resting upon table tops of various metals, and when insulated from table top during ether vaporization with a 1 liter flow of oxygen through the vaporizer.

portions to the total flow of other gases. This change in design was the most important concept incorporated in this vaporizer. It soon became apparent that the device which had been designed primarily for chloroform, would be useful for ether and other anesthetic agents normally liquid at room temperature. The vaporizing surface is a sintered bronze disk (Porex) which divides the gas passed through the vaporizer into a multitude of extremely small bubbles. The combined surface area of this multitude of bubbles is such that the time of exposure to the liquid becomes almost a negligible factor. A second advantage of the Porex disk is in the conduction of heat directly to the gas-liquid interface from the ambient atmosphere through the copper container and copper table top. Thus important principles have been combined to provide vernier control of concentration, efficiency of vaporization, and moderate thermostability (2).

In the design of this apparatus copper has been emphasized as necessary for the container. It is desirable that the table top of the gas machine be copper since this metal has both a high heat capacity and a high heat conductivity. The practical importance of the use of copper in this way is shown in figure 1 which illustrates the poor thermostable characteristics resulting from the use of steel as a table top or from insulating the vaporizer from the table during ether vaporization by a 1 liter flow through the vaporizer. As can be seen, insulating the copper vaporizer from the table top or utilizing a metal with less heat conductivity such as steel, detracts markedly from the thermostability of the apparatus. The superiority of the Porex disk as a vaporizing surface is shown in figure 2, compared with the Heidbrink wick, and the Foregger and Boyle's type bubble bottle. These others are obviously less efficient.

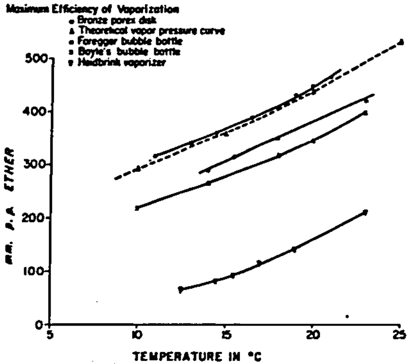

FIG. 2. Comparison of the maximum vapor tension of ether produced at various temperatures by the Copper Kettle, Foregger bubble bottle, Boyle's bubble bottle, Heidbrink wick vaporizer, with the theoretical vapor pressure curve for ether.

Considerations in the Usage of the Copper Kettle

The introduction of any new drug or piece of apparatus is not infrequently handicapped by the fact that the user subconsciously interprets observed effects and makes comparison in the light of previous personal experience with items considered to be similar but which in reality may require a different concept in their use. Since the introduction of the Copper Kettle to general usage, it has become apparent that incomplete understanding of some of the considerations involved has led to errors on the part of some users and manufacturers. Difficulties in use have been most frequently encountered because of either underestimating the potential output of the vaporizer, or lack of recognition of those factors which may lower the ether concentration below that which is expected. Inasmuch as the vaporizer will perform satisfactorily in any of the usual anesthetic systems or techniques if properly used, it may not be amiss to make some comments and offer some suggestions regarding ways of avoiding these difficulties.

The chief advantage of the circuit design is in the vernier control over increments in vapor concentration. The metered flow of carrier gas through liquid anesthetic in effect reflects the addition of increments of anesthetic vapors as though it were itself being metered as a separate gas.

Deaths have occurred during use of the Copper Kettle usually because of failure to appreciate the fundamental principles of its design. It must be realized that the outflow of vapor concentration from the vaporizer itself is lethal unless diluted, and may represent in the case of ether from 50 to 60 per cent or even 70 per cent concentration depending on the temperature of the liquid within the vaporizer.

Extreme caution is indicated when adding ether vapor to a closed system since the high concentrations provided lead to a rapid increase of lethal concentrations. In closed absorption systems therefore, only small flows of oxygen need be passed through the ether in the Copper Kettle intermittently to add adequate ether to the system. Additional oxygen for metabolic requirements should be added from the fine flow of the "oxygen only" meter, as needed. Some of the deaths which have resulted from the use of this apparatus have occurred simply because it is beyond the concept of the individual using the apparatus that such high concentrations could be built up so rapidly. Some older less efficient vaporizers, in which lethal concentrations are difficult to achieve, have allowed the development of a widespread concept that ether is a safe agent in the hands of even the inexperienced. Users of efficient vaporizers, such as the Copper Kettle, must abandon this fallacious reasoning and carefully avoid misuse of this effective device.

It is important to avoid thinking of the "oxygen-thru-ether" as oxygen. Particularly to be deplored is the modification which has been incorporated in some machines of this general design which allows the carrier gas without vapor to reach the patient when the double shutoff or exclusion valve is turned off. No one would ever think of using oxygen and cyclopropane through the same meter as a matter of preference. For the same reasons we must not get in the habit of thinking of the "oxygen-thru-ether" as being life-saving oxygen when in fact it may on occasion inadvertently, or because of some mental aberration of the anesthetist, be carrying a lethal concentration of ether or some other volatilized liquid anesthetic. Because of the flexibility in control which can be achieved with the Copper Kettle circuit and because of the versatility of anesthetic systems in which it can be satisfactorily used, ether becomes a "new" anesthetic agent, to delight the user in the ease of its control, lack of irritation and speed of induction.

As might be predicted, some dissatisfactions occasionally are expressed regarding the performance of the Copper Kettle vaporizer. These are usually due to some misuse or some misunderstanding of the capabilities of the device. The most frequent and most obvious difficulty is that of a leak. In a device known for its facility to produce high concentrations of ether, it is a source of annoyance and immediate dissatisfaction if these expected concentrations are not obtained. If ether is escaping to the atmosphere through some point other than the delivery tube, it is obvious that the patient will not become anesthetized regardless of what the meters on the machine indicate. Leaks may be found in the container itself, in the junction between the container and inflow and outflow, in the outflow tube, and not infrequently in the meters. The second most frequent difficulty is found in an obstruction to the outflow of the delivery tube. This allows an increase of pressure within the vaporizer itself, which in turn will be dissipated through a point of weakness not otherwise evident. For this reason it has been recommended that a delivery tube of not less than 5/16" internal diameter be used. The relative obstruction produced by a delivery tube of ¼" diameter from the anesthesia machine will result in a reduced concentration of ether at any given flow through the vaporizer. This factor must also be considered when using the device for insufflation of ether through an oral pharyngeal catheter. Such a catheter should be of the largest possible diameter. Use of a connecting tube with a narrow orifice must be avoided.

A difficulty which was encountered with some of the earlier models of this type of apparatus has been avoided by the introduction of an ether exclusion valve which shuts off both the inflow and outflow from the vaporizer. This is designed as a cam valve with positive action so that when turned off it will prevent a steady, continuous and annoying leak which is present in most other types of vaporizers. This exclusion valve is activated by the same lever which operates the oxygen flush for emergency use. It is apparent that under this circumstance the vaporizer must be turned off before the oxygen flush is turned on. This was designed deliberately, to avoid an inadvertent increase of pressure in the vaporizer during the time the oxygen flush valve is open, with a subsequent surge of vapor after the valve is turned off. The other possibility which is avoided by the cam valve is that of an injector action which could occur when the oxygen flush valve is open thus entraining vapor from the vaporizer. Either of these situations is obviously extremely undesirable under circumstances in which one is desirous of lightening the level of anesthesia in order to protect the patient.

Summary

Concepts which have been incorporated in the design of the Copper Kettle should not be irresponsibly abandoned. Correspondingly it is important that each individual user of this apparatus should appreciate the fundamental principles involved in the design of this precise tool for the production of anesthesia so that its maximum advantages can be utilized.

References

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