Hazards of Anesthetic Equipment

Edmond I. Eger, II, M.D., and Robert M. Epstein, M.D.

The anesthetic machine and system provide an environment common to both anesthetist and patient. This environmental factor can exert a significant influence on both persons. It is essential (1) that hazards inherent in equipment be eliminated and (2) that one understand the functions and limitations of such equipment. The most obvious dangers have long been eliminated from machines and systems; but hazards of varying degrees of subtlety remain, unfortunately only revealed by disaster or near disaster. Hazards of equipment result not only from mechanical failure but also from improper interaction between the operator and the machine. Finally, although defective equipment may be made secure once the defect is known, the dangers of misuse through inadequate knowledge of the functioning of equipment may occur even with perfect apparatus.

This paper will examine anesthetic equipment from several viewpoints. The anesthetic machine (tanks, valves, flow-meters, and out-of-circuit vaporizers) will be considered first, followed by an examination of anesthetic systems (open, semiclosed, and closed) including in-circuit vaporizers.

Anesthesia Machines

The function of an anesthetic machine is the preparation of gas mixtures of pure and precisely known yet variable composition. The mixture must be delivered into an anesthetic system in volumes appropriate to the characteristics of the individual anesthetic agents or techniques. This problem is complicated by the variability of the physical and chemical characteristics of the initial components; from compressed gases and liquids of high volatility to liquids of low volatility, from relatively inert substances to others which may burn, explode, or react chemically with their containers. These must be blended into gaseous mixtures of known composition for presentation to the patient. Anesthetic machines represent a hazard to the extent that they may fail in any of these functions, or introduce risks of direct physical trauma. Our discussion suggests, but does not exhaust, the many possibilities for injury.

Gas Sources

High pressure gas sources and the means of control have in the past represented a serious hazard. Early anesthesia machines lacked pressure regulators (reducing valves), and the airway could be subjected to full tank pressures. Machines without regulators depend on continuous readjustment of the needle valve to provide a relatively constant gas flow, because flow through the valve is roughly proportional to the driving pressure, and the orifice must therefore be changed as the pressure falls. If this precaution is overlooked, the composition of the gas mixture may change sharply. In addition, the opening of a new gas cylinder to replace one exhausted can result in dangerously high flow rates and the possibility of lung rupture, if the need to readjust the needle valve has been forgotten.

Most currently used pieces of equipment possess regulators to provide “safe” working pressures of oxygen and other gases. Failure of regulation is still a possibility owing to distortion of internal linkages or wear of high pressure valve seats (fig. 1). For this reason, high pressure regulators should be backed up by relief valves designed to open at somewhat higher than working pressures, commonly 100 p.s.i.

The danger of connecting the wrong gas to a cylinder manifold has largely been elimi-
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...ated by the introduction of the pin index system. Older machines are still in use, however, in which the adapters supplied have long since been missing. Obviously the risk of asphyxiation exists whenever another gas can be substituted for oxygen. Even with pin indexing, pipeline gas sources can be connected to the wrong inlet. This error has occurred where the connecting hoses came from a ceiling mount and the fittings were used in an upside-down position thus by-passing the index pins.5

Additional hazards from the use of high-pressure gas cylinders arise in their handling. Pertinent safety rules are not always heeded. Although steel cylinders are rugged, careless handling has transformed them on occasion into destructive missiles. Reports in the literature include descriptions of damage to cylinders resulting in the abrupt release of pressure and the scattering of large chunks of metal with killing force.6

The connection between oxygen cylinder and yoke must be free of dust and other potentially flammable substances. Before connecting a cylinder to the yoke, the tank should be “cracked” to flush out any such materials. Cylinder valves should be opened slowly to prolong the time during which compression of the gas between cylinder valve and the high-pressure end of the regulator occurs. In this way, the heat of compression is dissipated and the establishment of a shockwave prevented. Otherwise, the heat of compression together with a minute source of oxidizable material sets the stage for fusion of metals and resultant explosion.2-3 Shock waves (propagation of the pressure increase at greater than the velocity of sound) particularly must be avoided as the temperatures which they produce are substantially higher than those of simple compression.6 The cylinder valve must be opened widely even though slowly. Marginal opening of these valves may result in the failure to deliver gas when pressure has fallen only slightly. Lethal anoxia resulting from this error alone has been reported.7

A related hazard of compression occurs when gas cylinders are transfilled. The resulting high internal temperatures or the creation of flammable mixtures within cylinders have resulted in explosions. More than one anesthesiologist has been killed in this way. Aside from deliberate transfilling, the possibility of inadvertent transfilling exists between paired cylinders if the back-cheek valve in the cylinder yoke is defective. This defect occurs not infrequently and should be discovered by looking for backflow through the cylinder connection when empty cylinders are removed and changed.

Emptied oxygen cylinders are also a hazard and undoubtedly result in anesthetic catastrophe far more often than reported. In the midst of a host of other duties, as long as the anesthetist is forced to rely on repeated observation of his equipment to detect failure of his oxygen supply, he will on occasion err. We believe all gas machines should incorporate a fail-safe mechanism to interrupt the flow of asphyxiating gases when oxygen pressure is diminished. The system devised by A. S. J. Lee7 (fig. 2) continues to be satisfactory. Simpler systems have been devised which lack the feature of proportional control of all gas flow rates with oxygen pressure variations, but which provide a “gating” or on-off function that demands oxygen pressure for gas delivery. A recently demonstrated device of this type can be attached to the outflow line.
of the gas machine and should prove useful for modification of existing equipment if it becomes commercially available.

Pipeline sources of oxygen, although a great improvement over cylinders in both economy and safety, are nevertheless not a guarantee against an inadequate oxygen supply. Some connections can deliver gas without being positively locked to the machine. Consequent to movement of the machine or line, such connections may be dislodged. Similarly, many systems include cut-off valves in the operating room which when operated by well-meaning but poorly informed attendants have caused failure of oxygen supply and subsequent cardiac arrest. It is recommended that all such valves be locked in the open position and their handles removed. Valve controls against fire hazard and major leakage should be installed outside the operating room in “break-to-open” wall boxes. But complete security still demands the fail-safe principle.

Even a fail-safe system requires that the user turn on the oxygen flow valve. An interesting alternative approach to the prevention of anoxia from nitrous oxide inhalation is the suggested incorporation of an adequate concentration of oxygen (25 per cent or more) in the nitrous oxide cylinder. An early proposal of this nature supposed that the tank pressure would be limited by the vapor pressure of nitrous oxide, but it is now established that pressures approaching 2,000 p.s.i. are feasible. Apparently solution of oxygen in liquid nitrous oxide lowers the critical temperature of the mixture below room temperature so that both
nitrous oxide and oxygen exist in the gaseous state. Hence, a uniform gaseous composition is found to issue from the tank without fractional distillation of the components. Extreme cooling should be avoided to prevent condensation of nitrous oxide, but if it has occurred, a return to room temperature and inversion of the cylinder suffice to restore equilibration. Although this technique is applicable only to oxygen-nitrous oxide mixtures because of the flammability of other gases, its general adoption would increase safety. Further tests of the practicality of this idea will be watched with interest.

**GAS LINES**

 Interruption or obstruction of gas lines within anesthesia machines is uncommon. Some cabinet-style machines employ a rubber tube connection within the cabinet to facilitate storage of the canister and valve assembly. Kinking or separation of this line within the cabinet is not easily corrected and has been the cause of serious incidents occurring during anesthesia. To avoid accidents, flexible lines must be exposed throughout their length and should connect to fittings on the cabinet exterior.

 A more common and generally unrecognized problem is the presence of foreign bodies, in particular metal shavings and chips which are not removed after manufacture. These can play havoc with such units as check valves, regulators, and needle valves. A system of disposable filter cartridges located proximal to these critical units could protect them from foreign materials introduced into gas lines. Filters (incorporated downstream from wall-gas connectors) would seem particularly desirable as the supply hoses are frequently allowed to drag on the floor between usage.

**NEEDLE VALVES**

 Valves used to control the flow of gases often function inadequately. Behaving well at first, they later become erratic in performance, develop backlash, and lose the smoothness and precision of control over flow which is their function. The result is not only annoying but can prevent the delivery of desired concentrations or gas flows. High quality valves are mandatory.

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**Fig. 3.** Schematic diagram of a needle valve for flow adjustment. Accurate control over the gas flow is provided by the fine pitch of the valve threads at A, and by the narrow taper of the needle point at B. Wear at A results in play preventing positive setting of the valve. Wear at B increases the rate of change of orifice with rotation of the knob and decreases the precision of control.

The difficulty with valves arises in part from the designers' intention that they perform both a control and an on-off function (fig. 3). The latter results in scoring of the valve seat, and deformation of the needle. The practice of closing these valves after a tank is closed, when the zero point cannot be identified, fosters damage. The solution would seem to lie in the use, in series, of a lever operated (spring-closing) valve for positive on-off closure and a needle valve designed never to seat completely. For oxygen supply, the lever operated valve should be omitted, but the needle valve nevertheless should always provide a minimum flow, as there is never a need to use a machine without a flow of oxygen.

Control knobs should be of distinctive size and shape instead of the commonly supplied symmetrical controls. Erroneous selection and manipulation of control valves can and has occurred, especially when anesthesia is given under adverse conditions. A certain amount of de-systematizing is of value in increasing the safety and certainty of control.
Flowmeters are critical to the achievement of precision anesthesia. Meters in general use are of the taper-tube variety, either inclined with ball indicators or vertical with ball or float rotameters. These can and should be very precise. Precision within one percent of full-scale over a ten to one flow range is easily achieved. It is disappointing therefore to see anesthetic equipment with old-style short-scale blind flow tubes, tubes with compound tapers to permit scale compression, and similar sacrifices of readability and accuracy. Tubes should be of the full-length (10-12 inches) variety with nearly uniform taper. Extended ranges of flow can be achieved without major scale compression or multiple control valves by the use of flow-meters in series.

Even in high quality flowmeters, errors in flow can occur. Because clearances between float and tube are very small, especially in low range flow-meters, the float may stick. At this point, a minute particle of dirt can produce substantial meter errors by changing the effective orifice size. In the presence of such obstruction, gas flow will force the float to erroneously high levels. Moreover, a sticking float may yield either high or low readings or actually conceal the absence of flow. Floats should be designed to rotate and be marked to indicate rotation. Unfortunately, this is most difficult at the lowest flows at which clearances are smallest and errors most likely.

Flow tubes used in anesthesia machines are commonly made of glass to permit visual indication of flow. The neoprene (or similar material) gasket required for the glass-metal seal may be attacked by hydrocarbons, such as cyclopropane. The resulting deposit of decomposition products in a low-range low-clearance flow-tube frequently results in sticking or irregular oscillation of the float making reading impossible. Viton gasketing has been reversed and hypoxia prevented by the flowmeter arrangement illustrated in figure 4C or in 4D. By placing the oxygen flowmeter nearest the outlet, a leak at another flowmeter results in less of anesthetic gas rather than oxygen. Although this may not result in anesthesia at least it does set the stage for a potential disaster. (Reprinted with permission from Eger et al.\textsuperscript{11}).
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parenly been used with more success, but this too is not perfect. The problem of deteriora-
tion of materials may become a major one if halogenated gases such as enflurane are intro-
duced into clinical practice.

Glass flow tubes are subject to breakage which suddenly renders a machine unusable. More subtly, cracks and chips may occur and be overlooked with resulting errors in delivered flows. If the oxygen flow tube is involved, anoxia may result from the loss of oxygen. Eger and his co-workers pointed out another hazard of occult breakage. In their case a crack in an unused rotameter allowed oxygen to escape, while nitrous oxide, delivered down-stream from the cracked tube, was given to the patient (fig. 4). This accident can be avoided by having the oxygen flow tube last in the sequence prior to delivery of mixed anesthetic gases to the anesthetic circuit.

To our knowledge, flowmeter arrangement has resulted in at least two deaths when a float position was read beside an adjacent but wrong scale. Failure to associate a given scale with a given tube is common, the spacing of tubes and scales often being monotonously uniform. Color coding is not carried over into the flow tubes and the floats themselves. Even more confusing, the relative position of tube and scale, left and right, is sometimes variable among flow-meters in the same machine. Under such circumstances, errors are inevitable.

VAPORIZERS

The use of volatile liquid anesthetics requires devices to convert these liquids to a gas phase of known composition. Such vaporizers may be placed in the circuitry of the machine ("out-of-circuit") or in the respiratory circuit ("in-circuit").

Out-of-circuit vaporizers in use today are of several types. In the first of these (e.g., Flotec) the entire gas flow from the machine passes through the vaporizer which is designed to divert a fraction into a vaporizing chamber and to add the saturated vapor fraction to the total flow to achieve a known concentration. Because of the variability of vapor pressure with temperature, this has a thermo-compensating device which varies the bypass fraction to yield a fixed output at a given concentration setting within a wide range of temperatures.

The action of this type of vaporizer is intrinsically complex. The output concentration has proved stable and reproducible over long periods of time when measured at a constant flow and constant gas composition. Criticisms which may be leveled at these devices, however, include:

1. Systematic errors in concentration have been found in newly acquired vaporizers, although the output remains quite constant. We have measured errors as large as 30 per cent either above or below the indicated setting.

2. The concentration is distinctly flow sensitive below 4–5 liters per minute. To a lesser extent, the output varies with the input gas composition, increasing slightly when N₂O is used as compared to oxygen alone.

3. They can be used without recalibration for one agent only.

4. They are difficult to clean and in time "freeze" because of gummy, varnish-like deposits.

5. Loss of calibration accuracy is not readily recognized.

A second form of out-of-circuit vaporizer is the "kettle" type. In this, a flow of oxygen is bubbled through a liquid contained in a reservoir from which it emerges very nearly saturated with the vapor of the volatile agent. Knowing the temperature, the temperature-vapor pressure curve, and the volume of inflow gas, the volume of vapor emerging can be calculated. The dilution by main-stream gas then gives the concentration.

This vaporizer is versatile and has been used for a wide variety of agents. Unlike the total flow vaporizer, these are easily cleaned and the accuracy of calibration is essentially determined by the accuracy of flow meters. Properly used, they must always contain a thermometer to give accurate liquid temperatures for calculating vapor pressure. Some are supplied with thermometers not long enough to give representative readings, as they are situated high in the emerging gas stream. Furthermore, the flow rate available must be sufficient to provide an adequate volume of
vapor, particularly during the induction period. For agents of low volatility and high blood and tissue solubility, such as methoxyflurane, this requirement definitely limits the usefulness of the vaporizers that are currently available. For such agents, vaporizers with a larger total flow capacity would be useful.

Since this form of vaporizer produces a vapor output close to that predicted by the vapor pressure-temperature curve, no modification (short of application of heat) can be expected to produce a higher output concentration. In the face of this, it is disturbing that increasingly complex devices are being offered as “more efficient” or more effective. Inspection of the interior of one of these instruments revealed a percolating, spray-tower mode of operation. It is therefore no surprise that output concentrations greater than theoretically predicted have been found since droplet entrainment and eventual vaporization of droplets into the diluent gas flow may occur. A stream of liquid anesthetic has actually been observed to issue from another of these vaporizers.† The result—complete lack of control over the output concentration—is hazardous to an extreme.

Either type of vaporizer is subject to an additional inaccuracy when used in conjunction with positive pressure respiration. Intermittent fluctuation in line pressure results in a reversal of flow or “pumping” action which increases the volume of gas entering and hence that of the anesthetic emerging from the vaporizer. This problem is associated chiefly with low flows, as in closed system administration of halothane. Hill and Lowe have shown that the Mark II Fluotec can deliver approximately 3 per cent halothane vapor when set at 0.5 per cent and used with a 500 ml. per minute total flow rate and intermittent positive pressures of 20 cm. of water in a circle system. Its delivery at the same settings was only 0.2 per cent halothane into free air (i.e., no intermittent positive pressure). Similar pressure effects occurred with the “copper kettle” type of vaporizer. At high total flow rates (4 liters per minute) the additional halothane vaporized was somewhat greater, but the effective change in concentration was smaller because of the greater volume in which the extra vapor was diluted.

This effect can be prevented by incorporation of a valve in the outlet line so arranged as to prevent recycling of partially saturated anesthetic mixture through the vaporizer. The most effective of the suggested arrangements seems to be one in which the one-way valve is placed in the vaporizer outlet line (kettle vaporizer) upstream from the point of mixture with diluent gas (fig. 5). In this way, reflux of diluent flow into the vaporizer is prevented during the period of positive inspiratory pressure. The method employed with the Fluotec vaporizer required delivery of the entire vaporizer flow at elevated pressures. However, it should be emphasized that

* Personal communication, Hamilton S. Davis, M.D.
† Personal communication, Henry L. Price, M.D.
because this recycling effect is prominent only at low flow rates, it produces only a small volume of anesthetic vapor. Under this circumstance, the inspired mixture (from the rebreathing bag) differs substantially from the delivered concentration and the effect on depth of anesthesia is limited by the vapor available for uptake. Conversely, at higher gas flows when pulmonary ventilation is more of a factor in determining uptake, the effect of positive pressures on output concentrations from the vaporizers is less evident.

Many out-of-circuit vaporizer arrangements other than those treated here have been described. The scope of this review does not permit individual consideration of them, and the reader is referred to the literature for evaluation of their function and potential hazards.

Vaporization is proportional to flow through the vaporizer. For out-of-circuit vaporizers, flow is determined at the machine. For in-circuit vaporizers, flow is determined by inflow from the machine and by gas flow resulting from ventilation. This results in a stable anesthetic state when ventilation is spontaneous. For example, ventilation increases if anesthesia tends to lighten. With increased ventilation, the output of the vaporizer increases and the amount of anesthetic reaching the patient increases.\textsuperscript{19-21} Not only may the inspired concentration increase but, in addition, the alveolar concentration approaches that inspired due to the increased ventilation. Each of these factors tends to oppose the lightening of anesthesia. Similarly, deepening anesthesia decreases ventilation, decreases vaporized output, and thereby decreases inspired concentration.\textsuperscript{19-21} The alveolar concentration falls with the reduction in ventilation. The end result is that deepening of anesthesia is opposed.

This stability of the anesthetic state inherent in in-circuit vaporizer is eliminated when ventilation is changed from spontaneous to controlled. With ventilation held constant, any tendency to deviate from a steady anesthetic state is accelerated. For example, cardiac output decreases if anesthesia tends to deepen. With decreased cardiac output, there is a decrease in anesthetic uptake. Since less anesthetic is removed from the alveoli and the anesthetic system, the concentration in each tends to rise; and anesthesia deepens further. At low inflow rates, this cyclic deepening with controlled respiration—if unchecked—may progress to dangerous levels. The reverse, lighter anesthesia leading to still lighter anesthesia, also may occur. A point of particular hazard occurs when ventilation is changed from spontaneous to controlled. The increased output of the vaporizer that results from the increased flow causes a sudden deepening of narcosis. This must be anticipated and the shunt through the vaporizer reduced concomitantly with the increase in ventilation.

Twenty to thirty years ago the principle volatile anesthetic was diethyl ether. At this time, ventilation during anesthesia was usually neither assisted nor controlled. Both the inherent stability of such an anesthetic system and the slowness with which levels of ether could be changed regardless of the stability of the system made the in-circuit vaporizer acceptable. The introduction of rapid acting volatile halogenated anesthetics and the modern widespread use of controlled ventilation made the system using in-circuit vaporizer unstable. This, combined with the difficulty with which they could be calibrated, led to the abandonment of in-circuit in favor of out-of-circuit vaporizers. This situation has been mitigated with development of slower acting anesthetics of low vapor pressures such as methoxyflurane. These anesthetics must be inspired in concentrations approaching that of their vapor pressure to achieve rapid induction of anesthesia. Such a concentration is difficult to produce with out-of-circuit vaporizers but is easily developed with in-circuit vaporizers.

In contrast to in-circuit vaporizers, out-of-circuit vaporizers produce stability with both spontaneous and controlled ventilation if inflow rates are high (5 plus liters per minute).\textsuperscript{19-21} In this case, ventilation does not affect vaporization. In addition, uptake of anesthetic agent has a minimal effect on inspired concentration as long as ventilation is less than half to two-thirds of the inflow rate. When the inflow rate is low (less than three to five liters per minute) and particularly when the system is closed, uptake significantly alters the con-
centration of anesthetic inspired. With lightening of anesthesia, cardiac output rises and uptake increases. This lowers the inspired concentration and thus tends to result in lighter anesthesia. This is countered in part by the increase in ventilation which raises the alveolar concentration towards that inspired. Conversely, with deeper anesthesia, cardiac output and uptake fall and the inspired concentration rises. If respiration is spontaneous, the resultant decrease in ventilation offsets in part the increased inspiratory concentration. However, if ventilation is controlled, this compensatory decrease in respiration does not occur and anesthesia may become progressively deeper. This is an unstable anesthetic system with “positive feedback.”

The in-circuit vaporizer is usually placed on the inspiratory limb of the circle system. This produces an additional resistance to inspiration. The expiratory limb has been suggested as a better location since this would transfer the additional resistance to expiration where it is better tolerated. This also would dilute the vapor in the volume of the reservoir bag and thus prevent the sudden administration of a high inspired anesthetic concentration. However, the expiratory position of the vaporizer places the escape port between the vaporizer and the patient. Thus, part of the vapor leaving the vaporizer escapes before reaching the patient. In addition, inflowing fresh gas reaches the patient without passing the vaporizer. Both of these factors result in an inspired concentration far less than exists at comparable inflow and ventilation when the vaporizer is in the inspiratory limb. The discrepancy is great when inflow is high and essentially zero when the system is closed. Induction with soluble agents such as ether and methoxyflurane may be prolonged under these circumstances (vaporizer in expiratory limb).

## Table 1

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<tr>
<th>Reservoir</th>
<th>Rebreathing</th>
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<tr>
<td>Open</td>
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<tr>
<td>Semiopen</td>
<td>Yes</td>
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<tr>
<td>Semiclosed</td>
<td>Yes</td>
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### Anesthetic Systems

The function of an anesthetic system is to deliver to the lungs the gaseous mixtures supplied by the anesthetic machine. In so doing, the anesthetic system must not compromise the inspired oxygen tension nor should it permit the inhalation of appreciable concentrations of carbon dioxide. There should be little or no resistance to ventilation. The system chosen may or may not permit assisted or controlled respiration; may not allow precise control of the inspired anesthetic concentration; may not be economical of anesthetic gases; and may not be simple in construction. But these are ancillary to the main function of an anesthetic system: the presentation of the anesthetic mixture to the patient.

The nomenclature devised by Moyers is used here (table 1). Although a great deal of overlap exists among categories, the classification is one into which any anesthetic system may be placed.

### Open Systems

These include open drop, insufflation, and the Ayre T-piece without a reservoir. These are the simplest of the anesthetic systems: therein lies their virtues and their limitations. It is unlikely that these devices will be mechanically defective. Their cost is low, rebreathing imposed on the patient absent (except under a mask) resistance to breathing minimal, and heat dispersal maximal. Yet these devices are used much less frequently than the more complex anesthetic systems. This lack of popularity results from several inherent problems. The principal one is the difficulty in maintaining a stable anesthetic state. Whatever anesthetic is administered is diluted more or less by admixture with room air. Dilution is greatest when flow from the machine is low. The amount of dilution is dependent on the volume and character of respiration; a large minute volume and high inspiratory flow rate produce the greatest dilution. The greater ventilation (and hence dilution) becomes, the closer the alveolar anesthetic concentration approaches zero. Increased ventilation of the lungs either through stimulation or a slight decrease in the anesthetic concentration administered thus results in greater dilution and lightening of anes-
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Thesia. Lighter anesthesia leads to a further increase in ventilation and eventually results in an inadequately light level of anesthesia. Although this may be a source of embarrassment, it is not always a hazard. However, depression of respiration decreases air dilution and thereby increases the inspired concentration of anesthetic. When the inspiratory flow rate falls to or below the flow rate of insufflated anesthetic, then the maximum inspired concentration (i.e., the inflowing concentration) is reached. If this increase in inspired concentration is not balanced by anesthetic uptake, the alveolar anesthetic concentration must rise. This in turn results in deeper anesthesia and further respiratory depression. In addition, deeper anesthesia reduces cardiac output and anesthetic uptake is thereby lowered. If unchecked, anesthesia continually deepens until ventilation becomes inadequate. Thus the patient who becomes lighter tends toward an even lighter plane, while the patient who becomes deeper continues in this direction. The open systems, as opposed to all others, are invariably unstable, possessing what might be called positive feed-back.

Another major disadvantage of the open system is lack of control over ventilation. No means for positive pressure ventilation are available except with the T-piece where the end may be occluded intermittently by the finger and the lungs inflated by the gas inflow. This in itself is potentially dangerous since the upper limit of pressure applied may exceed several atmospheres (line pressure) — more than enough to rupture a lung. Such a possibility can be prevented by insertion of a pressure limiting valve in the inflow source. In any case, it is impossible to adequately assist ventilation even with the T-piece since the inflows commonly used are well below peak inspiratory flow rates. Therefore, during spontaneous respiration an attempt to assist ventilation by occluding the outlet produces inspiratory obstruction. It is also more difficult to monitor ventilation with an open system since one of the simplest (but gross) indicators, the movement of a reservoir bag, is absent.

Dilution of anesthetic gases by room air may be dangerous, particularly if respiratory depression exists. As shown by Faulconer, the inspired oxygen tension and arterial oxygen saturation may be deficient with open drop techniques unless additional oxygen is insufflated under the mask. Other disadvantages of open systems under certain circumstances include a drying effect on mucous membranes and maximum heat loss. The hazard of fire or explosion is relatively greater with these devices than in closed or semiclosed systems since the major portion of the anesthetic delivered is vented to air. Finally, the system is wasteful of anesthetic agent.

**Semiopen Systems**

These include the Rees modification of Ayre's T-piece (fig. 6), the Magill apparatus (fig. 6B), and the use of nonrebreathing valves. These devices have eliminated some of the principal hazards and disadvantages of open systems, but unfortunately have introduced some of their own. By precluding dilution of inspired agent with room air, inspired concentration is held constant and the instability of the anesthetic state inherent in the open system is eliminated. Addition of a reservoir bag permits controlled or assisted ventilation and provides a visual and tactile impression of depth, rate, and rhythm of respiration.

The Rees T-piece and the Magill apparatus are dependent upon flow to prevent rebreathing, while with nonrebreathing valves rebreathing is unlikely so long as the valve functions properly.

Both open and semiopen systems impose
little resistance to breathing when properly used. However, nonrebreathing valves may “cut off” inspiration if inflow to the reservoir bag is inadequate. An exception is the Frumin valve which is arranged so that the expiratory check valve will open if airway pressure becomes negative. This allows inspiration of room air which if overlooked introduces the instability of an open system. Fluctuations in ventilation must be allowed for by excess inflow when a nonrebreathing system is used.

Most valves currently available are so constructed that the escape valve automatically closes when positive pressure is applied. It is possible that an excess or sudden high inflow of gas may build up sufficient pressure to “lock” the escape valve. This may occur when changing abruptly from controlled to spontaneous ventilation in which situation apnea or hypoventilation may persist for several minutes. Sudden high inflow may occur on “flushing” oxygen into the reservoir bag. Unless the pressure in the reservoir bag is decreased to release the locked valve, inflow will cause a continuous rise in pressure until the bag or the patient’s lungs are ruptured. This can be prevented by inserting a pressure limiting device (vent) within the nonrebreathing valve or in the inflow source. Such a valve in the inflow source should open at slightly elevated pressure and should automatically close to permit intermittent positive pressure breathing. The Georgia valve or the pressure equalizing valve described by Steen and Lee seem to meet these requirements.

Since both the Rees T-piece and the Magill apparatus depend on adequate inflow rates (2+ times the minute volume for the former and 1+ times for the latter) for elimination of carbon dioxide, a hazard of rebreathing exists with lower flows. Controlled ventilation with the T-piece does not result in a decrease in $P_{CO_2}$ commensurate with increase in ventilation since rebreathing usually occurs and increases with increasing ventilation. Reduction in alveolar $CO_2$ is limited by the ratio of inflow to alveolar minute volume during spontaneous respiration. For example, if inflow were 6 liters/minute and the initial alveolar minute volume were 3 liters/minute, alveolar $P_{CO_2}$ would not fall below half its initial value regardless of how large the volume of controlled respiration. At least, with the unmodified T-piece, controlled ventilation produces a fall in alveolar $P_{CO_2}$; with the Magill apparatus the converse may occur because the gas expelled through the expiratory valve is the inflowing fresh gas. The inflow rate commonly used in this system is equal to the minute volume. Therefore, the loss of fresh gas before it can be used for respiration means that alveolar ventilation must be reduced an amount corresponding to the fresh gas lost. The change from spontaneous to controlled respiration with this device thereby increases rebreathing out of proportion to the increase in ventilation. A rise in alveolar $P_{CO_2}$ and a fall in $P_{O_2}$ result.

The Rees T has a hazard common to all adaptations of Ayre’s apparatus: since the inflow enters at the patient’s airway, any obstruction to escaping gas causes inflation of the lungs by the inflow: the pressure limit is the line pressure. Obstruction may occur either at the connection between the T and the reservoir bag or at the exit of the bag. Both have resulted in ruptured lungs. A pressure limiting valve at the T or in the inflow line would prevent this.

Minor hazards and drawbacks of semiclosed systems are the same as those for open systems: heat loss and dessication, and the high flows required may be prohibitively expensive, especially when these systems are used for adults. Drying may become a major problem in nonrebreathing endotracheal anesthesia, especially in infants and children where occlusion of the endotracheal tube by encrusted mucus may occur.

**Semiclosed and Closed Systems**

Semiclosed and closed rebreathing technique made possible by the to-and-fro and the circle—

—Personal communication, Robert B. Sweet, M.D.
absorption systems reduce or eliminate most of the drawbacks of the semiopen and open systems. As noted above, both open and semiopen systems are wasteful of anesthetic gases. In addition, rebreathing may occur with the Rees T-piece and the Magill apparatus. Used properly, semiclosed and closed absorption systems provide the advantages of economy, carbon dioxide removal, ease of observing and controlling ventilation, and minimal heat loss and drying. Rate of inflow of gas into these systems is no longer crucial. Under certain conditions (see above under vaporizers), they promote a stable anesthetic state.

The To-and-Fro System. The to-and-fro system (fig. 7) is the simpler of the rebreathing systems. It is similar to the Rees T except that a carbon dioxide absorber is inserted between the inflowing gas hose and the reservoir bag. The to-and-fro system is little used today because it is cumbersome and because of the hazard of accumulating carbon dioxide upon exhaustion of a small fraction of the absorbent. The explanation for rebreathing is as follows: absorbent nearest the patient becomes inactive since all expired gases traverse it. This becomes a dead space. As anesthesia proceeds, this space progressively enlarges, perhaps causing the patient to breathe more and more deeply and thereby increasing his carbon dioxide output and alveolar carbon dioxide tension. This situation is mitigated by the rate of inflow which, if sufficiently great (twice the minute volume), washes out the expired carbon dioxide. Conversely, the increase in dead space is progressive if low flows are used.

In operation, the to-and-fro canister usually is placed on its side. Unless uniformly packed, channeling occurs along the upper length of the canister and inadequate carbon dioxide absorption results. This also increases dead space. Placement of the canister at the mask or endotracheal tube permits the inhalation of absorbent dust if the dust is not removed prior to connection of airway and canister. This dust is extremely irritating owing to high alkalinity and inhalation may produce laryngospasm, bronchosospasm, or cough. It has not been shown that tissue damage occurs.

Inflow and outflow in the to-and-fro system are usually located as indicated. Reversal of inflow and outflow positions as originally suggested by Waters results in an arrangement similar to the Magill apparatus. Inflow rates equal to or exceeding the minute volume, reduce or eliminate the need for absorbent.

The Circle System. The circle-absorption system (fig. 8) is the most complex anesthetic system in use. By causing the flow of gases within the system to travel in a circle, the major defects of the to-and-fro system are eliminated. Carbon dioxide may be removed at a distance from the patient, thereby eliminating the cumbersome handling of the canister at the patient's head. Expired gases must traverse the entire length of the absorber rather than a variable distance as in the to-and-fro system.

The general arrangement of the circle system is determined by considerations of safety and economy. The reservoir bag must be excluded from the patient's respirations by inspiratory and expiratory valves. That is, the exhaled gas must pass a valve before reaching the reservoir bag and the gas inhaled from the reservoir must pass a valve before reaching the patient. If the valve system is accidentally by-passed or omitted, the patient then breathes directly from the reservoir through the connecting tubes. Rebreathing with hypercapnia results. If an excess of oxygen is not present in the gas mixture, hypoxia also results. Inadvertent omission of valves from a circle system has been reported. Arterial pH at the time of discovery of omission was 6.72 with a calculated arterial Pco2 of 234 mm. of mercury.

Inflowing gases are usually introduced between the inspiratory valve and the patient so that all fresh gas reaches or bypasses the patient before arriving at the outlets of the system. A better position is the introduction just proximal to the inspiratory valve (i.e.,
inspiratory valve between inflow and patient). At a given inflow, this produces an inspiratory gas mixture containing the greatest possible proportion of fresh to previously exhaled gas. The outlet needed when inflow exceeds the volume of gas absorbed by the patient is usually placed between the patient and the carbon dioxide absorber. In any event, it must never be placed between the inspiratory valve and the patient. The latter arrangement results in increased rebreathing of gas previously exhaled since exhaled air may move retrograde into the inspiratory tubing. During spontaneous respiration, the optimum position of the outlet is at the patient because the end-tidal gas will be that discharged. However, during controlled ventilation, this outlet position apparently results in spillage of fresh rather than end-tidal gas. For general use, the outlet is best placed so that a corrugated tubing lies between it and the patient. At higher inflow rates requiring discharge, a certain amount of exhaled gas then escapes through the outlet before reaching the absorber. This reduces the amount of carbon dioxide to be removed by soda lime and not only prolongs the life of the absorber but also reduces the magnitude of hypercarbia that the absorber would have become exhausted.

If the components of the circle system are positioned as described, hazards resulting from their use usually result from malfunction or misuse. Rebreathing of exhaled carbon dioxide follows inadequate absorption. This may be the result of incompetent valves, channelling through the absorber, or exhaustion of absorbent. With large canisters, because of the baffle system used, the effect of channelling is small and the time of efficient carbon dioxide absorption is prolonged. Such absorption remains effective for 15 to 20 hours in a closed system at ordinary rates of CO₂ production. Prior to introduction of the large canister, the tendency was to change the absorbent more frequently than necessary: the reverse may be true today.

The hazard of inhalation of soda lime dust is reduced in the circle as opposed to the to-and-fro system. The interposition of the connecting corrugated tubing between canister and patient permits the dust to "settle out" before reaching the patient, adhering to the walls of the tubing if wet. The possibility of inhalation of soda lime dust is also reduced by the larger diameters of the newer canisters. The larger cross section lowers the flow velocity with less turbulence and formation of dust.

Soda lime may also react with trichlorethylene in the presence of elevated temperatures to produce toxic breakdown products. This possibility is so widely appreciated that the direct use of trichlorethylene in the presence of soda lime is a rare accident. However, a patient (for example, in labor) who has inhaled this agent for analgesia may then be anesthetized with another agent. If a circle system is used, the soda lime may then react with the trichlorethylene exhaled by the patient. Another way in which trichlorethylene and soda lime might indirectly be brought into contact relates to the high solubility of trichlorethylene in rubber. If the rubber tubing and bag used to administer this agent are subsequently used in the presence of soda lime, release from rubber and reaction with the absorbent may take place.

Misfunction of valves may occur in two ways: (1) they may fail to open properly or completely, or (2) they may not close properly. Wetting of a valve causes it to stick. The expiratory valve is usually wet and resistance to expiration may occur at this valve unless constructed of nonwettable material. A valve may be held open by a foreign material. In older machines, granules of soda lime occasionally were found holding a valve open. In dome valves, the valve may adhere to the dome when wet unless a guard prevents the valve from reaching the dome or the valve is nonwettable. Since a permanently open valve provides less resistance to flow than a closed valve which must open, respiration may take place entirely through the incompetent side. As noted above, this may result both in hypercarbia and in hypoxia.

The use of monitoring devices, such as the Monaghan ventilation meter, or sampling devices, such as the Otis-Perrin end-tidal sampler, introduces one or more extra valves into the circle system. Ventilation is not impeded if these are correctly placed, permitting gas flow as directed by the inspiratory and expiratory valves of the circle. However,
if the extra valves are placed so as to oppose flow, either inspiration or expiration or both may be prevented. This is most hazardous if expiration is impeded and inflow gases have no vent. Lung volume then increases at the rate of inflow until rupture occurs. This, of course, is prevented by a pressure limiting valve in the inflow tract.

Semiclosed or semiopen systems present a potential hazard which may be found when inflow is high and outflow occurs through a spring loaded valve or through a constricted orifice (the tail of a bag, for example). Outflow is then a function of pressure. As the reservoir bag is squeezed, outflow increases. This gives the illusion of ventilation, that is, of gas entering the lungs, when in reality all may be vented to air. Complete airway obstruction may thus not be diagnosed until cardiac arrest appears. The illusion of ventilation may be eliminated by the use of an outflow valve which automatically closes during inflation.

The reservoir bag and corrugated tubing rarely present hazards. In prolonged anesthesia, the expiratory tubing may become partially filled with water condensed from expired gas. If enough water condenses to occlude the expiratory limb, partial obstruction to expiration occurs. This is accompanied by a bubbling sound on expiration as exhaled gas is forced through the water.

It is important that the rubber used in anesthetic equipment be conductive since non-conductive rubber is conducive to the production of a static charge. A spark produced may be disastrous in the presence of a flammable anesthetic. The conductivity of rubber is subject to deterioration. The authors have even found newly purchased bags marked "conductive" to be excellent insulators. There is no substitute in this case for direct testing of conductivity. A simple and inexpensive conductivity meter could become an integral part of an anesthetic machine.

Summary

The anesthetic machine and system link the anesthetist to the patient and hence form an environment common to both. By these means, the anesthetist induces and maintains anesthesia. Where defects exist, they constitute a greater or lesser hazard to the patient, and at times to the anesthetist. Some of these hazards are due to the possibilities of direct physical trauma such as may arise from combustion or the unleashing of high gas pressures. Others are due to inaccuracy in the composition of the breathing mixtures provided the patient. These may arise from errors in the design, construction or in the use of a gas machine.

In addition, hazards due to inaccuracy in the composition of the inspired gas mixture or interference with respiration may arise in the respiratory circuit. The machine and system used by the anesthetist do not act independently of the patient. The patient is an active recipient who reacts to and acts on this imposed anesthetic environment. Changes in ventilation, circulation, and the uptake of anesthetics have been shown to affect the composition of the gas offered the patient. The nature of these changes is itself affected by the particular anesthetic system employed and by its manipulation. A thorough understanding of the nature of such interactions permits an increase in the precision with which anesthetics may be administered, and reduces the hazards of anesthesia.

References


