THE CHEMICAL ABSORPTION OF CARBON DIOXIDE FROM ANESTHETIC ATMOSPHERES * †

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During the two decades just past, the use of completely closed respiratory systems for the administration of anesthetic gases and vapors has received extensive clinical trial. Certain advantages of such a system have been demonstrated. One of these is the reduction possible in the quantity of volatile and gaseous agents necessary to maintain anesthesia by inhalation (1) or to maintain therapeutic concentrations of gases such as oxygen (2, 3, 4). There is general agreement that the decreased amount of agent necessary to maintain anesthesia or effective therapy over long periods, as compared to the otherwise necessary "open" administration, results in a substantial saving, variable and dependent upon the technical facility of the administrator and the mechanical perfection of the apparatus.

The saving of variable amounts of materials, however important in civilian medicine, is greatly magnified in military practice. Under such circumstances, the weight and bulk of supplies and equipment may influence the choice of drugs and methods; a circumstance which would be deplorable. In applying this method to anesthesia and to other therapeutic procedures, certain mechanical errors have been made. Mistaken conclusions have been drawn from past experience. It seems fitting at this time, therefore, to reconsider what has been written and revise our concept of the carbon dioxide absorption technic.

Historical Aspects

Perhaps it is desirable in such a discussion to include a brief mention of certain historical facts which have escaped attention in previous publications. It is of interest to know that a completely closed respiratory system was utilized in the study of the exchange of gases even before the work of Priestley (5), Goodwyn (6) and Lavoisier had clarified our knowledge of the physiology of respiration. Scheele (7) performed the following experiment (fig. 1). He confined bees with a bit of honey in an atmosphere of oxygen exposed to lime water. The bees utilized the honey and the oxygen to support anabolism while the carbon dioxide produced was absorbed in the lime water. It is of no

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less interest that John Snow, within five years of the introduction of surgical anesthesia (8), applied the closed respiratory system of Regnault and Reiset (9) in the study of the amount of carbon dioxide produced both by animals and by himself while breathing normal atmospheres and also those rich in oxygen and containing anesthetic agents. He observed that a quantity of chloroform, which would affect him for only two or three minutes by open inhalation, could thus be made to last for twenty minutes. However, he did not seem to grasp the import of the use of this technic in the clinical administration of anesthetics. He was interested chiefly in the effect of these agents upon the activity of oxidative processes—the amount of carbon dioxide produced normally and during anesthesia.

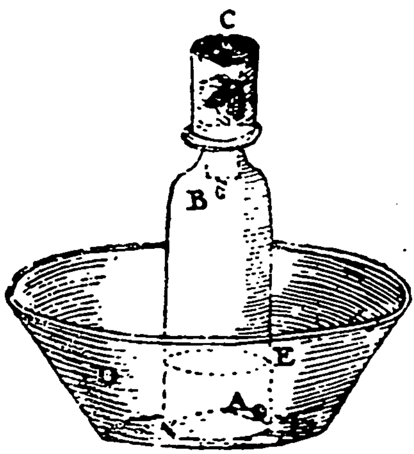

FIG. 1. Scheele's experiment (before 1775). Bees, honey and oxygen in the glass vessel, inverted in lime water.

Theodor Schwann is said to have demonstrated an apparatus in 1853 (fig. 2) before the Belgian Academy of Sciences which utilized two one-way valves to cause the respired atmosphere to circulate in one direction. Carbon dioxide was absorbed by "potassa." Oxygen was supplied from two small pressure cylinders carried in the pocket. He presented it as a closed system of respiration which might solve the problem of mine rescue work in the presence of poisoned air. A model of this apparatus was seen by the author in the Deutches Museum at Munich in 1936. The illustration is made available by the kindness of the museum director.

The first reliable experiments which I have found described in the

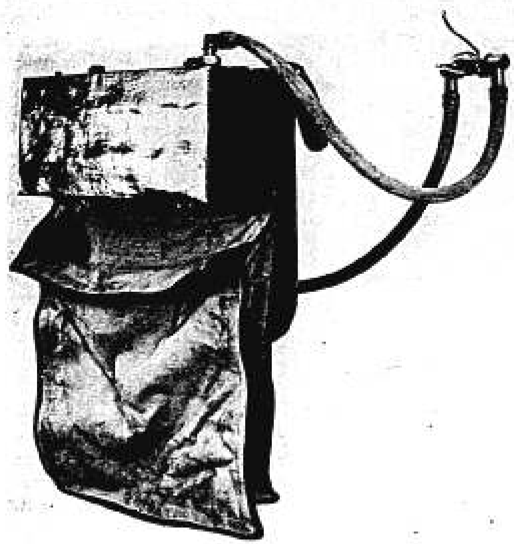

FIG. 2. Model of a closed respiratory system seen in the Deutches Museum (Munich) and attributed to Theodor Schwann (1853). Large tray of alkali with breathing bag and two one-way valves carried on the back. Mouth piece connected to it by two large breathing tubes. Oxygen supply in pocket.

literature, directed specifically at the conservation of anesthetic gases and vapors, are those of Jackson (10) referred to in previous communications. It is obvious that the idea of chemical removal of carbon dioxide is far from new. In view of present knowledge, the rejection of some of the early attempts to apply the absorption technic is self-explanatory. The apparatus which Franz Kühn (11) described in 1906 (fig. 3) is an example. The extremely long, single tube between airway and alkali creates, of course, an unphysiologic volume of dead space from which carbon dioxide is not absorbed. Apparatus with the same fault in varying degree may be purchased at the present time.

PAST EXPERIENCE WITH THE CHEMICAL ABSORPTION OF CARBON DIOXIDE FROM CLOSED RESPIRATORY SYSTEMS

The Chemical and its Container

The experiments of Wilson (12), continued to date by the manufacturers Dewey and Almy and others, have resulted in making available reasonably satisfactory soda lime for that purpose. The size and character of granules chosen must be correlated with the size of the container in which the atmosphere is exposed to chemical action and with the time of contact allowed for such exposure. The presence of dust in material which has been carelessly handled still constitutes a hazard. When using the to and fro technic, meticulous care must be used that no soda lime dust be blown into the respiratory tract or conjunctival sac. Construction of apparatus by manufacturers, at the request of individuals, without exhaustive experimental investigation, has been costly.

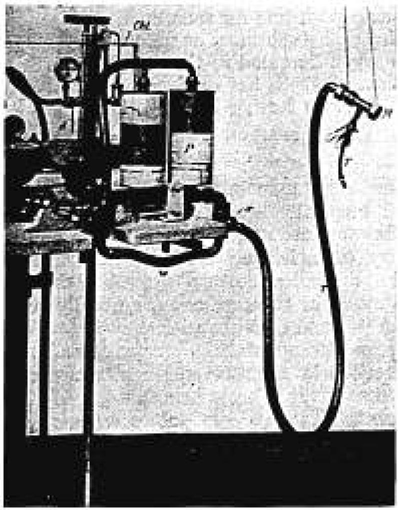

FIG. 3. The mechanically imperfect apparatus suggested by Franz Kühn (1906) for the administration of anesthetics in a closed system. Note the long, single breathing tube between the airway and the "circle" contact with the canisters of "caustic."

The efficiency of absorption, the amount of dead space, the possibility of resistance to breathing, and many other factors should be checked carefully before a change is accepted.

Recent attempts to add a dye to soda lime as an indicator (13, 14), in the hope of offering a warning when chemical efficiency is exhausted, have proved disappointing to the author. The addition of an indicator to the granules does no harm but the use of a transparent canister has scarcely seemed justifiable in routine work. The information gained from the change in color of the indicator is not always reliable from the point of view of efficiency. Chemical analysis of the atmosphere in the face mask, airway or bronchi for its content of carbon dioxide has been suggested as a safeguard. Such tests are easily made and are essential in determining the adequacy of any new equipment of modified construction. Analysis of samples taken from the apparatus at a distance from the patient are worse than useless since results may give a false sense of security. Only the atmosphere actually inhaled by the patient is important. Under operating conditions, no chemical tests can safely replace the meticulous and discriminating observation of the patient by the anesthetist.

A less bulky substance, effecting a more rapid chemical reaction, might be found as a substitute for soda lime. The possibility has been studied of utilizing such a substance as sodium peroxide for the purpose, employing the oxygen liberated in the reaction to replace the oxygen used by the patient (15). It has received no attention in recent years. This suggestion deserves further investigation.

The Apparatus

From the practical standpoint, there are two arrangements of apparatus by which a completely air-tight system can be maintained and through which the contained atmosphere may be brought in contact with alkali. Each requires a leakless contact with the upper respiratory tract of the patient through a face or nose mask or through a pharyngeal or tracheal airway. The two methods are usually referred to as the "circle" and the "to and fro" technics.

The circle device (16) maintains a constant circulation of the atmosphere in one direction by means of (1) two "one-way" valves, (2) a pump, or (3) by use of the injector principle.

One-Way Valves.—Two one-way valves were employed in the apparatus of Schwann. Early devices (17) for the measurement of oxygen consumed by patients, as a basis for the calculation of metabolic rate, applied this method of assuring contact of expired atmosphere with alkali. The metabolism laboratory early abandoned the use of valves because of (*a*) the inevitable resistance to breathing; (*b*) the annoyance to conscious patients of the sound made by the closing of the valves, and (*c*) the tendency of such valves either to leak or to "stick." Objections (*a*) and (*c*) are valid for unconscious patients and (*b*) remains an annoyance in anesthetic apparatus during induction. Pumps to circulate the atmosphere are now utilized in all metabolism apparatus. In spite of the experience of the expert in studies of metabolism, anesthetists have employed the principle extensively, probably because the manner of connecting the apparatus with the patient's airway is not radically different from that used in anesthetic machines previously familiar to them.

Pumps.—Reluctance to include an electric motor in apparatus which must contain explosive mixtures is rational (1, 18). Pumps activated by water pressure and hand power, in our experience, have proved satisfactory for experimental investigation (19) although cumbersome when used in the operating room.

The Injector Principle.—Application of the injector principle, utilizing the pressure of compressed nitrous oxide as it enters the closed system to circulate the respired atmosphere, has been utilized in an apparatus designed by Crafoord (20). The possibility of maintaining adequate circulation on the injector principle, using the amount of oxygen added to maintain metabolic requirements of the patient, may be worthy of experimental study by American manufacturers.

In the *to and fro device,* soda lime is placed in a container between the airway or mask and the rubber breathing bag (18, 21, 22, 23, 24). With connections of adequate caliber and proper relation of granule size to container size and construction, the resistance to breathing to and from the bag through the soda lime granules is negligible (13). At the same time, adequate contact is provided to permit sufficient chemical absorption of carbon dioxide.

Comparison of Circle and To and Fro Methods.—Both the circle and the to and fro principles are in daily use in the administration of anesthetic agents in many parts of the world. This could scarcely be true if both systems did not give reasonably satisfactory clinical results for the average patient. When the patient is debilitated or seriously ill, it is often difficult to evaluate the possible harm that may result from any particular factor of the many affecting the patient during an operation. For this reason, ill effects due to disturbed respiratory function are all too frequently assigned to other sources. It must be admitted that no apparatus of either type now in use is completely free of mechanical defects when applied to certain patients.

Convenience and safety are promoted by having the whole respiratory system, including the breathing bag, in the field of vision of the anesthetist and in close proximity to the patient. When breathing is depressed, manual augmentation of respiratory exchange can be accomplished by intermittently pressing on the bag with the hand. Adequate respiratory exchange is essential to maintain normal bodily functions. In a majority of instances, unphysiologic depression can be prevented by care in the selection and dosage of agents. When manual augmentation of respiratory exchange is found necessary, too frequently it may be an admission of the anesthetist's lack of skill. If "control of respiration" (24) is considered by the anesthetist as essential in providing satisfactory working conditions for the surgeon, he needs only to exaggerate the bag compression (suggested as a remedy for depressed breathing) during a few inspiratory phases of the respiratory cycle. By so doing, the concentration of carbon dioxide at the respiratory center will be reduced below the threshold of sensitivity. An apneic state will result which is similar to that following a period of voluntary and extreme hyperpnea in a conscious individual. Complete inactivity of the patient's respiratory muscles will obtain. Now, if the anesthetist will continue intermittent rhythmic pressure on the rubber breathing bag, *in a manner simulating normal exchange,* adequate function of respiration may be maintained for any desired period without the resumption of activity of the patient's respiratory muscles. Many anesthetists find it difficult or impossible to perform this technic properly unless the to and fro apparatus is used. Again, the importance is emphasized of having the movements of the patient's chest and of the breathing bag both in the visual field of the anesthetist. "Manual augmentation" and "controlled respiration" are special technics to be used only for specific reasons; the former to correct an inadvertent overdose of drug, and the latter in an effort to provide more ideal working conditions for the surgeon. The result of either procedure upon the welfare of the patient will depend upon how skillfully the anesthetist is able to imitate "normal" ventilation for that particular patient at that time.

Addition of accumulated body heat to the heat resulting from chemical action, when carbon dioxide and water vapor combined with alkaline substances may result in temperatures of inspired atmosphere as high as 40 or 45 C., ranges definitely unpleasant to the conscious patient. The tendency toward such accumulation of heat is greater in the to and fro technic. This has so far proved a contraindication to the application of this method in therapeutic administration of gases over long periods to conscious patients. Since time is required to accumulate heat, the factor is of no moment during the induction of anesthesia. The physiologic effect of the inhalation of warm atmospheres, and of atmospheres saturated with water vapor, as in both arrangements under discussion, deserves more detailed study. Clinical observation indicates some advantage to the patient from inhaling warm, moist atmospheres as contrasted with those which are cold and dry as in open technics of administration. The similarity in appearance of apparatus utilizing the circle principle to that used in "open" technics formerly popular, and the technical novelty in the proper application of the to and fro method have made for slow and reluctant acquisition of skill with the latter by many older anesthetists. For the present, it must remain an open question whether the "circle" or "to and fro" technic is preferable. Personal experience of the author to date is strongly in favor of the use of the latter principle.

Meters

Small quantities of agents are dealt with when utilizing chemical absorption; hence the importance of the development of meters capable of indicating delicate changes in the rate of flow of oxygen which is added to replace that utilized by the patient from the closed system. If the best results are to be secured in the use of cyclopropane, a similar delicate indication of quantity flow is necessary for that agent. Whether a "dry" or a "wet" flowmeter will ultimately prove more satisfactory is yet to be determined. In England, advantages are claimed for the "rotometer" (14). I have had no personal experience with this appliance. The principle is one well recognized in mechanics. Its application to anesthetic and therapeutic apparatus deserves further study in this country. Continuous accuracy, ability to withstand rough usage, and freedom from the need of repair are the qualities needed in such meters.

Dead Space

Air-tight airways attached to absorption systems constitute a replacement, in part at least, of the upper respiratory tract of the patient. Masks constitute a certain addition to the physiologic "dead space" of the respiratory tract. Connection space to the soda lime canister or one-way tubing may materially increase the volume of such added dead space (13). Details of construction of apparatus for the application of both arrangements (circle and to and fro) have received too little attention by manufacturers and anesthetists. It should be obvious that the exit of tubing of "circle" apparatus from the side of the face mask or airway and the "entrance" of the returning atmosphere on the opposite side of the mask or airway would reduce dead space. The importance of eliminating unnecessary dead space cannot be overestimated. Drug action in anesthetized patients always tends to result in reduced ventilation and therefore in high tensions of carbon dioxide in blood and tissues (23, 24, 25, 26, 27). Central threshold sensitivity to carbon dioxide is raised. Any added dead space further disturbs an already abnormal carbon dioxide relation. The customary utilization of oxygen tensions, above those in the atmosphere to which the patient is accustomed, tends also to increase respiratory acidosis (24, 26, 28).

The anesthetist who utilizes the carbon dioxide absorption technic by either arrangement of apparatus must therefore maintain a constant awareness of the fundamental physiologic disturbances which may be taking place in his patient. When trouble develops, although his first thought, as always, must be of deficiency of oxygen from respiratory obstruction or depression, his next move must be to determine the probability of inadequate elimination of carbon dioxide. Too much dead space for a particular patient, especially in children or those whose respiratory activity is depressed by drug action, is a frequent cause of serious physiologic disturbances. Early evidence of excess of carbon dioxide in the tissues may be manifest by increases in blood pressure, sometimes by a more rapid pulse rate. Convulsive manifestations are usually seen at some stage of carbon dioxide accumulation. Activity of small muscles about the face may precede actual convulsions. The depression of sedative drugs, however, often masks many or all the signs of poor elimination of carbon dioxide. The manufacturer has paid too little attention to the factor of individualization of apparatus. This does not excuse the physician if he overlooks technical faults which permit physiological imbalance in his patients. The anesthetist should alleviate functional disability when it exists. In any case, he should not permit such conditions to be made worse by his efforts.

The Atmosphere

Clinical experience and some laboratory investigation (19, 29, 30, 31) tend to show that patients suffering from disturbances of metabolism are subjected to further strain when breathing abnormal atmospheres. The temptation is great, when using the absorption technic, to utilize a mixture of gases considerably different from the 20 per cent oxygen and 80 per cent nitrogen to which the average patient is acclimatized. When there is evidence of a deficiency of oxygen in the tissues, concentrations of this gas higher than 20 per cent are, of course, indicated during anesthesia just as they are in the care of such patients before and after operation. However, there is reason to believe that anesthetic atmospheres will cause the least amount of physiologic disturbance when they are constituted of gas tensions as nearly approaching those of room atmosphere as is possible while maintaining adequate concentration of the anesthetic agent (32). Considerable evidence is accumulating to show that biochemical disturbances of a somewhat serious nature may occur when the atmosphere breathed by a handicapped individual is suddenly and markedly changed. Many anesthetists believe that when a decidedly abnormal atmosphere is necessary during anesthesia the shift to room air should be made slowly and gradually. Further search for proof of this belief is desirable.

Possible Ignition of Anesthetic Atmospheres.—Obviously, hydrocarbon gases or vapors mixed with oxygen or nitrous oxide in a closed respiratory system are not likely to be ignited from a source outside the system so long as it remains closed (1). The danger from illuminating gas flames, alcohol lamps, cauteries and other electric equipment is therefore dependent on the care with which the closed respired atmosphere is maintained without leaks. With cooperation between surgeon, operating room attendants, and anesthetist, the need to interrupt the closed system can be avoided at all times when sources of ignition are near to the apparatus. There remains to be considered the possibility of static sparks acting as a source of ignition inside a closed system or at the instant when the respiratory system is being opened or closed. Such accidents have occurred (33).

Mixtures of explosive agents which contain high tensions of oxygen or of nitrous oxide are more readily ignited than are mixtures containing the 20 per cent of oxygen which exists in room atmosphere. We have here, then, a physical as well as the above mentioned physiological reason to avoid anesthetic atmospheres containing higher tensions of oxygen than are needed to maintain adequate oxygen for the requirement of the patient. However, one should not infer from this fact, as some recent publications (34, 35) might be misinterpreted to imply, that subnormal tensions of oxygen used as a measure of prophylaxis from ignition are justifiable. The physiologic accident of hypoxia, or anoxia, is infinitely more frequently encountered in clinical practice than is the accident of fire or explosion. Deficiency of oxygen may as easily prove fatal although the death may be less spectacular.

There is considerable disagreement regarding some of the physical principles involved in the accumulation of differentials of static charge on the separate parts of inhalation apparatus. Humid atmosphere as a conductor of electric charges (36) and hence as prophylaxis from the development of a difference of potential on two different parts of apparatus has again come into question. Some engineers now deny the value of humidity. Physicists have suggested that radium may aid in preventing the accumulation of static charges in areas exposed to its emanations. Experiments are now in progress to determine both the effectiveness and the safety of such prophylactic employment of radium. It has been suggested that an atmosphere completely free of carbon dioxide does not conduct electricity (36). The experimental backing for this statement needs verification. However, the latter point is, in any case, largely academic because experience has shown that atmospheres in closed respiratory systems, just as in the case of the room atmosphere, are rarely if ever free of traces of carbon dioxide.

Metal objects in direct contact are known to equalize their static charges rapidly. For this reason, complete metal "intercoupling" between patient and anesthetist and all the various parts of the apparatus has been suggested (36). The possibility of such efforts failing to prevent accumulation of variant static charges when one connection is accidentally omitted, or when a break in such added metal connections accidentally occurs (37), has given the impression to some, including myself, that efforts at artificial intercoupling of all objects may constitute an added hazard. Those holding this view feel that the anesthetist will, in maintaining contact of the various parts of the apparatus with each other and with the patient, create a natural unit of physical contact. If he will, then, make and break all contacts of various units of apparatus with each other and with the patient while his hand is in contact with both parts, we believe the opportunity for a spark will be eliminated.

It is my personal belief that if a fire or explosion occurs while the to and fro type of closed respiratory system is in use, it will be found that the management suggested above has been incomplete in some detail. I cannot express so much confidence regarding the circle type of apparatus. The number of parts which move and may require to be connected and disconnected is greater. Moreover, the container of the closed respired atmosphere is partially outside the visual field of the anesthetist. In any case, we are all human and may inadvertently violate what we know and accept as correct practice. Especial awareness of the ignition hazard must therefore be maintained when we are hurried or fatigued.

SUMMARY

The principle of the chemical absorption of carbon dioxide from closed respired atmospheres is as old as our knowledge of the gaseous exchange which constitutes respiration. Its extensive application to the therapeutic administration of gases awaits a more perfect solution of the mechanical difficulties of maintaining contact of such closed systems with the respiratory tract of the patient without discomfort or inconvenience. The application of the principle to closed anesthetic atmospheres has, since 1923, extended to all parts of the world. Hundreds of thousands of patients have been anesthetized by the method. The saving in materials, as compared with "open" and "semi-open" methods, is of a high order.

In a world gone mad with military preparation, bulk and weight of supplies and equipment may determine whether or not inhalation anesthesia or inhalation therapy can be utilized. Efforts of the physicist, the mechanical engineer, the physiologist and the anesthetist ought to be combined with those of all clinicians and manufacturers in a joint determination to make this technic safely and conveniently applicable, not only to the administration of anesthetics but also to the treatment of respiratory accidents and illness, and to the maintenance of artificial atmospheres for aviators, divers and those who must work in poisoned air. Until more perfect apparatus is made available, safety in the use of the carbon dioxide absorption technic must lie in the intelligence and skill of the physician who utilizes the method.

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