

DISPOSAL OF CARBON DIOXIDE FROM DEVICES USED FOR INHALATIONAL ANESTHESIA

JOHN ADRIANI, M.D.

THE disposal of carbon dioxide from any inhaler, whether it be open, semiopen, semiclosed or closed, is not the simple matter that it appears to be at first glance. In open systems as free an egress as possible must be provided for the escape of exhalations. In closed systems, since there is no free egress, the elimination is accomplished in one of two ways. The carbon dioxide may be expired through a one-way valve to the outside atmosphere, or it may be removed by chemical filtration or absorption. No matter how effective the method of elimination may be, some CO_2 is certain to be rebreathed because it is virtually impossible to displace all of it from any enclosure which is placed about a patient's face. In laboratory studies using a mechanical ventilator at a 500 ml. tidal exchange, the reviewer¹ found as much as 0.25 ml. (out of a total of 10 ml.) CO_2 was rebreathed when a Yankauer mask covered with six layers of gauze was placed over the expiratory outlet. The least rebreathing occurs with the insufflation techniques, provided there is no obstruction to the expired gases.

TYPES OF INHALERS

Various classifications have been proposed for inhalers, none of which is wholly practical. The writer prefers to classify them simply as semiclosed and closed. Any inhaler which communicates with the outside atmosphere, either by a valve or a port, may be classed as a semiclosed inhaler. Any tight fitting inhaler which completely excludes the outside atmosphere is a closed inhaler. The expired and inspired gases remain within the system and are rebreathed. In these CO_2 is customarily removed by chemical filtration.

Semiclosed Inhalers. Semiclosed inhalers are of two types, those which permit rebreathing or recirculation of the respired gases and

Dr. Adriani is Director, Department of Anesthesiology, Charity Hospital, and Professor of Surgery, Tulane University, School of Medicine, New Orleans, Louisiana.

those in which there is no rebreathing, except the contents of the mask, or recirculation. In the latter type, often referred to as the non-rebreathing or semiclosed inhaler, each expiration is ejected into the mask and to the outside atmosphere through a unidirectional valve. Each inspiration consists of the mixture in the mask combined with a fresh portion of gas drawn through a second valve from a reservoir or supply line. In this type the prescribed gas mixture must be supplied at a flow rate which meets the inspiratory demand of the subject. This is accomplished by providing a continuous flow of the mixture into the reservoir or an intermittent flow from a demand valve. The disposal of carbon dioxide from a noncirculating demand-type of inhaler is adequate provided the valves seal properly and regurgitation or backlash does not occur. Improper sealing of the valve located between the reservoir or supply line and the mask causes regurgitation which is tantamount to increasing the dead space.² The "nonbreathing" technique assures the inhalation of gas mixtures of unvarying composition and permits rapid wash-out of unwanted gases, such as nitrogen from the lungs.³ It is, however, wasteful, particularly when expensive gases and vapors, such as cyclopropane and halothane are used. In order to avert this waste, semiclosed inhalers are frequently used, which permit a certain degree of recirculation and rebreathing and the use of flow rates less than the minute volume exchange of the subject. In these, the valves between the reservoir and the face piece are omitted. The exhalation valve is partially constricted by spring loading or by decreasing the size of the aperture, so that only a fraction of the expired gases is ejected from the system. The amount of CO_2 ejected with each expiration is less than the quantity the patient is excreting. Therefore, a build-up of CO_2 of serious proportions may occur unless proper steps are taken to avert this. Not only is CO_2 retained in such a system but also the oxygen

tion in the inhaled mixture may be reduced to dangerous levels particularly when an 80 per cent gas and 20 per cent oxygen mixture is supplied to the system. Furthermore, nitrogen washout is delayed and often incomplete. Two arrangements of semiclosed inhalers are recognized, the to-and-fro consisting of a face piece and a breathing bag, and the circle type consisting of corrugated tubes, unidirectional valves and a breathing bag. In the circle type a third valve is necessary to permit ejection of the expired gases to the outside atmosphere. Adriani, Swartz and Mih³ and Miles and Adriani⁴ studied the effects of varying the flow rates of both arrangements of semiclosed inhalers upon inspired oxygen tension, CO₂ disposal and nitrogen washout. They found that in both the to-and-fro and the circle arrangement adequate oxygen tensions and satisfactory CO₂ elimination are not possible unless the gas flow rates into the inhaler are equal to or greater than the minute volume exchange of the subject using the inhaler. In a typical experiment using a flow rate of one-fourth the minute volume exchange (10 liters) and 200 ml. CO₂ per minute excretion, the concentration of CO₂ rebreathed was 5.5 per cent. At a flow rate of one-half the minute volume exchange the CO₂ rebreathed was 1.6 per cent. At three-fourths the minute volume exchange the CO₂ rebreathed was 1.8 per cent. At the minute volume exchange the concentration rebreathed was 0.3 per cent. At one and one-half times the minute volume exchange the carbon dioxide rebreathed was 0.2 per cent. At double the minute volume exchange the concentration was .05 per cent. Others have reported similar findings.⁵⁻⁷ The principle also applies to younger subjects whose inspiratory volumes are less than those of adults. The minute volume exchange or more must be provided to obtain an effective washout of CO₂ and nitrogen and effect adequate oxygenation. Chemical filters placed in either the to-and-fro or circle arrangement remove all the CO₂ except that in the face piece which is rebreathed.

In these same studies the oxygen tension, using a 20 per cent oxygen-80 per cent nitrogen mixture, fell to less than 15 per cent within 3 minutes at one-fourth the minute volume exchange of the subject. The arterial blood

oxygen saturation fell from 95 to 70 per cent. At flow rates corresponding to one-half and three-fourths the minute volume exchange of the subject, the oxygen tension increased proportionately but was still below the physiologic minimum. Only when the flow rate was equal to or greater than the minute volume exchange of the subject did the inhaled oxygen concentration in the mask reach and remain at 20 per cent. Adding oxygen to the mixtures so that percentages greater than 20 per cent were admitted to the inhaler at the lower flow rates corrected the anoxia.

It is customary to place the expiratory valve in semiclosed inhalers on the face piece. In the circle type, it may be placed anywhere in the circuit distal to the face piece. The location of the expiratory valve appears to make no difference as far as the excretion of CO₂ and elimination of nitrogen from the system are concerned. Likewise, varying the size of the breathing bag from 4 to 6 liters caused no appreciable difference in the facility for the elimination of CO₂. It appears, thus, that the problem of adequate oxygenation and proper CO₂ disposal in semiclosed inhalers, when using flow rates below those of the minute volume exchange of the patient, can only be solved by enriching the oxygen mixture with oxygen and absorbing CO₂ with chemicals.

Closed Inhalers. The terms "complete rebreathing," "the closed system" and "carbon dioxide absorption" are often used to designate techniques using closed inhalers utilizing the principle of chemical filtration of CO₂. The chemical filtration technique permits complete enclosure and rebreathing of gases and, therefore, possesses obvious advantages over the open and semiclosed methods. Some of the obvious advantages are economy, the fact that the warmed gases and vapors are inhaled, fluctuations in depth of anesthesia are not abrupt, flammable mixtures are confined and the use of positive pressure is possible. There are disadvantages also. The heat from the chemical reactions may be excessive. The apparatus is more complex than semiopen or open devices. There is a possibility of inhaling alkaline dust. The accumulation of CO₂ may result from inefficient removal. Some inhalational agents are altered chemically by the absorbent.

HISTORY OF CHEMICAL ABSORPTION

More than a quarter of a century has elapsed since Waters⁸ adopted the chemical absorption of CO₂ for the rebreathing technique of anesthesia. Waters was not the first to employ the method and disclaims any credit for being the first.⁹ Nonetheless, the method failed to receive acceptance until he introduced it. The enthusiasm for cyclopropane, which he introduced clinically in 1933, without a doubt did much to popularize the technique. Indeed, his introduction of the method antedated the acceptance of cyclopropane by nearly ten years, during which time the method was employed sporadically and for the administration of closed ether anesthesia.

The history of CO₂ absorption extends back many years.^{10,11} Scheele in 1777 was probably the first to use CO₂ absorption in an experimental manner in living things. He placed bees and a small amount of honey in a glass jar inverted over lime water. The water rose into the jar to replace the oxygen consumed by the bees. The CO₂ eliminated by the bees was absorbed by the lime water. In 1789 Antoine Lavoisier carried out his classical experiments on metabolism and showed that guinea pigs placed in a chamber eliminated CO₂. He absorbed the CO₂ with caustic soda. In 1847 Regnault and Reiset applied the same principle to larger animals. Dogs were kept alive in a closed chamber for several days. Oxygen was added and CO₂ was absorbed with slaked lime. In 1850 John Snow¹² inhaled chloroform vapors with a closed apparatus containing potassium hydroxide to abstract the CO₂. He also used CO₂ absorption for anesthesia in animals. He demonstrated that CO₂ output is decreased during chloroform and ether anesthesia. In 1853 Schwann prepared an airtight breathing apparatus for mine rescue work. This consisted of an inhaler containing alkali for absorbing CO₂ and an external source of oxygen. This is probably the first apparatus of a completely closed type designed for rebreathing or for controlling the gaseous exchange in humans. Alfred Coleman,¹⁰ a dentist, about 1871, designed an inhaler of a to-and-fro type with which he administered nitrous oxide to dental patients. He used slaked lime as the absorbent. Benedict¹³ in 1909 described a circle system

using soda lime as the absorbent for CO₂ in his important researches in metabolism in man. Dennis Jackson¹⁴ in 1915 used a closed circle system for the administration of nitrous oxide to dogs. He also devised a circle system for use in surgical patients but was unable to interest clinicians in adopting it. In his laboratory work a pump forced the exhaled gases through aqueous solutions of alkalis which absorbed the carbon dioxide. Brown and Foregger in 1909 and later Brindley and Foregger¹⁶ in 1923 experimented with sodium peroxide as an absorbent and as a source of oxygen. They were interested in its use in submarines. Sodium peroxide reacts with water to form sodium hydroxide and at the same time liberates oxygen. The alkali absorbs the exhaled CO₂. The volume of oxygen liberated is not in proportion to the amount of CO₂ absorbed. Therefore, the hope that oxygenation and CO₂ absorption could go hand in hand was not realized.

All these attempts to introduce CO₂ absorption were sporadic and not fruitful. Then Waters entered the scene. Taking a cue from Jackson, he applied the principles of chemical absorption of CO₂ to clinical anesthesia. In his early attempts, patterned after the laboratory experiments of Jackson, he employed a closed circle arrangement consisting of an aqueous alkaline solution, through which the exhaled gases were forced mechanically.¹⁷ Later the mechanical device was discarded in favor of the circle type filter. Still later he abandoned this and adopted a direct to-and-fro system which now bears his name.⁸ Finding a suitable absorbent was one of the problems which confronted Waters. This he solved by the adoption of soda lime developed by Dewey and Wilson for gas masks in World War I to anesthesia.⁸ More is said of this later. In 1929 Brian Sword¹⁸ devised a circle filter which was, in many respects, similar to the filter devised for use in man by Jackson. The Saad type (flutter) rubber valves was used to assure a unidirectional flow through the canister. The circle system was adopted by Heidbrink,²⁰ McKesson, Connell,⁹ and others in subsequent years.

In 1939 Adriani and Rovenstine²² performed laboratory investigations on CO₂ absorption. They observed that in the to-and-fro

filter absorption was most efficient when the expired tidal volume equalled the air space in a canister filled with soda lime. They noted that efficiency decreased when the air space was greater or less than the tidal volume. They also observed that the relationship of canister size to tidal volume also applied to the circle filter. They noted that absorption was not satisfactory when the air space in the canister was less than the tidal volume, however, they noted that absorption continued to be effective if the air space in the canister was greater than the patient's tidal volume and that canisters could be made as large as desired.

The absorption technique was introduced at a time when the use of the semiclosed system with rebreathing was commonplace. The ill-effects of hypercarbia were only appreciated by a few twenty-five years ago.²³ In fact CO₂ was considered by some to be beneficial.²⁴ It was not uncommon for anesthetists to deliberately add it to anesthetic mixtures. The contrast between the hyperventilation using the semiclosed system and the quiet breathing using the absorption technique was so striking that imperfections of the closed system anesthesia was not appreciated for some time. Adriani and Roventine,²² then later Conroy and SeEVERS,²⁵ indicated that CO₂ was not completely removed in either type of unit except for short periods of time early in the use of a charge of absorbent. Gradually it was realized that certain patients tolerated the incomplete removal of CO₂ better than others. This led to a reappraisal of CO₂ filters and total removal of CO₂ has become the present day aim.

In recent years Brown and Elam²⁶ have written extensively concerning CO₂ absorption. They too have conducted laboratory studies, as did Adriani and Roventine²² and Conroy and SeEVERS²⁵ and have reiterated and reaffirmed the findings of these earlier workers. They have stressed the advantages of using a circle system and large canisters. They have advocated using a divided canister so that full advantage may be taken of the absorption capacity of the alkali. The absorbent at the inlet half becomes exhausted before that in the distal half. Division of the canister permits discarding the exhausted portion, shifting of

the partially exhausted half into the inlet position and replenishment of the outlet half with fresh absorbent. This proposal has considerable merit and is being widely adopted.

A detailed description of the to-and-fro or the circle system is unnecessary in this review since both types of inhalers are familiar to all. Mention of certain details concerning the basic mechanisms of operation, however, is necessary. The to-and-fro system is used to a far lesser extent than the circle system. Beecher and Todd²⁷ noted that the circle filter was used in 95 per cent of the inhalational anesthetics administered in a group of nearly half million surgical patients in ten major teaching institutions in the United States. In the Waters canister the exhaled gases pass from the face piece through the canister over the absorbent to the breathing bag. During inhalation the gases reverse their flow and pass back to the face piece. The gases in the to-and-fro unit are in constant motion except for a brief interval during the expiratory pause when they become stationary before reversing their flow. During part of the expiratory pause the gases come to rest. Each expiration of an adult breathing twenty times per minute occupies approximately three seconds, provided breathing is regular, and inspiration equals expiration. Inspiration occupies a somewhat longer time interval than expiration as a rule. The inter-respiratory pause comes at the end of expiration. This may occupy up to 0.3 of a second. These figures, of course, may vary from patient to patient and from moment to moment, even in the same patient. In any event the period during which the gases are at rest is brief in the to-and-fro unit.²⁸ In the circle filter the gases move into the canister during expiration. In view of the unidirectional flow they come to rest and remain at rest until the next expiration. The flow into the canister, therefore, is pulsatile. During inspiration the filtered gases are drawn from the bag towards the mask and not from the canister. At the end of expiration the newly expired gases force the gases from the previous expiration further into the canister, if the canister is large or out of the canister if it is small. The gases remain at rest during the expiratory pause and during all of inspiration. This is

a period of less than $1\frac{1}{2}$ seconds. Longer contact with the absorbent occurs in the circle filter than in the to-and-fro.²⁵

THE CHEMISTRY OF ABSORPTION

Various chemical substances have been advocated and used for absorption of CO_2 . However, reliance is largely placed upon the hydroxides of the alkaline and alkaline earth metals.²⁵ Other substances are either less effective or impractical. Experiences with some of these other substances will be mentioned later in this review. The absorption of CO_2 by alkali is nothing more than neutralization of an acid by an alkali. Gaseous, non-metal oxides, such as CO_2 , sulphur dioxide and hydrogen sulphide form acids in the presence of water. These oxides, therefore, are anhydrides of acids. Metal oxides, on the other hand, are anhydrides of bases. They, therefore, combine with water to form hydroxides. Hydroxides in the presence of water actively combine with acidic gases. The ease with which alkalis absorb CO_2 and other acidic gases depends upon the activity of the metal forming the hydroxides. The activity is determined by the position of the element in the electromotive series. The most active hydroxides are those of the alkaline metals, since they occupy the uppermost position in the electromotive series. In the order of declining activity of the alkali metals are cesium, rubidium, potassium, sodium and lithium. Sodium hydroxide is the most extensively used hydroxide of the alkaline metals because it is highly active, abundant and relatively inexpensive. Potassium hydroxide, though more active than sodium, is used to a lesser extent because it is less abundant and more expensive and hygroscopic. Lithium hydroxide has been used for absorption of acidic gases for military purposes but it has not been generally accepted for anesthesia. The other alkali metals are less abundant and, therefore, are not used.

Alkaline Earth Metals. Next in activity to the alkaline metals are the alkaline earth metals. The order of activity of these is barium, strontium, calcium and magnesium. Of these barium and calcium hydroxides are the most serviceable. Strontium is more active than calcium but less abundant. Mag-

nesium hydroxide is not sufficiently active to effectively absorb acidic gases in closed inhalers. Other metals are lower down the series and, therefore, less active. The hydroxides of aluminum, zinc, copper, silver, gold and other metals are not sufficiently soluble or active to effectively absorb CO_2 quantitatively from anesthetic mixtures.

Formation of Carbonic Acid. Carbon dioxide first combines with water to form carbonic acid. Therefore, water is an important ingredient in the reaction of absorption. The water must be incorporated in the absorbent itself otherwise absorption is not satisfactory. Neutralization is the union of hydrogen ions with hydroxyl ions to form undissociated molecules of water. The carbonic acid, therefore, must dissociate into a hydrogen and carbonate ion. The base yields hydroxyl ions. Once hydrogen and hydroxyl ions unite to form water, the union is firm and the reaction is irreversible. The dissociation of water molecules into hydrogen and hydroxyl ions is slight. At room temperature only one molecule in 10,000,000 dissociates into hydrogen and hydroxyl ions. Carbonic acid is a weak acid. Only a small fraction dissociates into carbonate ion and hydrogen ion. The bases are highly ionized. In other words, they are almost completely dissociated into the metallic ion and the hydroxyl ion. As soon as water forms from the union of the hydroxyl and hydrogen ion, the equilibrium between undissociated carbonic acid and its ion is disrupted. The process of neutralization of carbonic acid is a comparatively slow one, since each molecule of acid must wait its turn to dissociate, so to speak, so that it can combine with the hydroxyl ion. A strong acid would be totally dissociated and more quickly neutralized.

The reaction of neutralization is exothermic; therefore, heat is evolved. This heat, referred to as the heat of neutralization, is a constant quantity and amounts to 13,700 calories for each mole (18 grams of water formed). The caloric output during neutralization may vary from several hundred calories per mole one way or the other, depending upon the degree of ionization of the acids and bases which interact.

The metallic ion (a cation) forms a salt with the acidic ion (anion). In the case of

carbonic acid the salts formed are sodium and calcium carbonates. The hydroxides of sodium and potassium are both very soluble in water. In fact they are so hygroscopic that they form gelatinous solutions when exposed to moist air. Sodium hydroxide dissolves in its own weight of water to form a saturated solution. The saturated solution of sodium hydroxide at 25 C. has a strength of approximately 20 molar. The alkaline earth hydroxides are far less soluble than those of the alkali metals. One gram of calcium hydroxide dissolves in 11.6 ml. of water at 25 C. One gram of calcium hydroxide dissolves in 630 ml. of water at 25 C. The ionization of barium hydroxide is almost as great as that of sodium hydroxide, however (92 per cent). The more dilute a solution is the greater is its dissociation. Thus, barium hydroxide is a strong base. It is more effective as a neutralizing agent than calcium hydroxide because it is both more soluble and more active. Aqueous suspensions of barium, calcium and magnesium hydroxides are referred to as milk of barium, lime or magnesium respectively. The supernatant liquids are saturated solutions of their respective hydroxides. Even though the hydroxides are poorly soluble they are strongly basic because they are highly ionized. They are less caustic than the hydroxides of sodium and potassium because of the diluteness of the solutions formed. All four carbonates of the alkaline earth metals are almost totally insoluble in water. Exposure of lime, barium and magnesium water to the slightest trace of carbon dioxide yields a milky cloud. Barium carbonate is less soluble than calcium carbonate and calcium carbonate is less soluble than that of magnesium. The carbonates of the alkali metals, on the other hand, are all water soluble. Sodium carbonate forms two hydrates, a decahydrate and a monohydrate.

Miscellaneous Absorbents. Attempts to use other chemicals besides soda lime for absorption have been disappointing. Ammonia absorbs CO_2 but is a volatile, feeble and irritating base and, therefore, of no value. Organic amines are, like ammonia, alkaline substances but nonvolatile. They have been investigated as possibilities as absorbents.²⁹ The results thus far have been disappointing. Absorption with ion exchange resins derived from poly-

merization of phenols and other organic compounds has been investigated by Derrick.²⁹ He found that the removal is not quantitative and, therefore, is incomplete. Besides the resistance offered to the ambient gases due to smallness of the particles of the ion exchanger is too great. Disposal of CO_2 by the use of adsorbents, such as silica and activated charcoal, likewise, is not feasible from a clinical standpoint.³⁰ The hydroxides of zinc and aluminum dissolve in an excess of sodium hydroxide to form soluble zincates and aluminates. These are alkaline and effectively absorb carbon dioxide but are not superior to soda lime. Besides they are more difficult to handle.²⁰

SODA LIME

Development. The first absorbents used for CO_2 were aqueous solutions of sodium hydroxide, powdered slaked lime and mixtures of calcium and sodium hydroxide in varying proportions. It was apparent to the early investigators that slaked lime was not an efficient absorbent and that alkali metal hydroxides were impractical because of their caustic and hygroscopic nature. An absorbent known as shell natron consisting of sodium hydroxide moulded in the form of sea shells was used.²⁵ Sodium and potassium hydroxide sticks likewise have been used. These are ineffective because of their hygroscopic nature and because they quickly become coated with sodium carbonate on the exterior. The interior remains un-neutralized because CO_2 does not penetrate the film. A preparation used in the laboratory for absorption consists of asbestos impregnated with sodium hydroxide (ascarite).²³ This is effective because the porosity of the asbestos presents a large surface to the alkali. It is too caustic for clinical use. Besides it is expensive. The early workers found that satisfactory results were obtained when mixtures of sodium and calcium hydroxide were employed. These mixtures were referred to as soda lime. Soda lime is a mixture of several chemicals and not a specific compound. Early in the use of soda lime, these mixtures consisted of equal portions of sodium hydroxide and lime. However, these mixtures were not satisfactory for clinical use because of the hygroscopic nature and

the high heat of solution of sodium hydroxide. Excessive heating and "caking" was encountered. Improvement in alkaline absorbents was precipitated during World War I by the need for an alkaline absorbent for use in gas masks when poisonous gases were introduced as a tactical weapon. Wilson¹⁵ and other U. S. Army engineers of the Chemical Warfare Service developed a soda lime which was a satisfactory absorbent for acid gases. Several years after the war Waters adopted this soda lime for anesthesia purposes.¹⁵

The soda lime used for anesthesia is a highly refined product. The ingredients used in its preparation must be of good grade and reasonably pure. The calcium hydroxide must be prepared from a high grade of calcium oxide, free from contamination with the oxides of magnesium, aluminum and other metals, since the latter decrease the efficiency of the product. Wilson found that the proportion of sodium hydroxide could be as low as 5 per cent before any significant reduction in absorption capacity occurred.¹⁵ Mixtures containing more than 5 per cent sodium hydroxide, although more efficient, cause excessive heating and caking. The calcium hydroxide is the mainstay of the absorption and performs the bulk of the work. In some of the European clinics absorbents of higher sodium hydroxide content are used.

Hardness. Soda lime pulverizes and fragments easily. Wilson and his associates preserved the shape of the granules and particles by adding silica (SiO_2).¹⁵ Silica (silicon dioxide) is the anhydride of silicic acid. Calcium hydroxide and sodium hydroxide react with this oxide to form silicates. Calcium silicate is a hard, glass-like compound. Sodium silicate is water soluble and forms a gelatinous hydrate. The greater the quantity of silica added the greater the degree of hardness. Unfortunately the capacity for absorption decreases inversely with the hardness. The hardness is usually determined by agitating a weighed portion of the absorbent with steel ball bearings in a steel pan, known as a hardness pan.¹⁵ The mass is then sifted over a 8-mesh screen and the unfragmented granules are then weighed. The per cent of the weight of the original sample remaining on the screen, expressed as a number, is known

as the hardness number. The hardness number should be greater than 75.

Size of Granules and Resistance. The size of the granules is an important factor in absorption because efficiency depends upon the surface area of absorbent presented to the reacting gases. The smaller the particles the greater the total surface area for a given mass of alkali which is presented to the ambient gases and the more effective the absorption. The converse is likewise true, the larger the granules, the less the surface presented for a given mass and the poorer the absorption. The size of the granules also influences the degree of turbulence which develops as the gases move through the canister. The finer the granules the greater turbulence and, therefore, the greater the resistance. Soda lime used for anesthesia is a blend of granules varying in size from 4 to 8 mesh. The larger 4-mesh particles comprise about 6-8 per cent of the total. The bulk of the mixture consists of 8-mesh particles. Obviously the percentage of granules of different sizes will vary with the product produced by a given manufacturer. The larger the granules the less the resistance. A fine soda lime (20-40 mesh) is often employed in devices used for determining basal metabolism. These inhalers are equipped with blowers to force the gases through the absorbent to overcome the resistance. The resistance offered by soda lime is, comparatively speaking, insignificant. The resistance offered by 1 kg. of 6-8-mesh soda lime is less than 1 mm. of water.²⁸ The resistance due to valves, angulation of tubes, narrow ports and so on is far more than that due to the particles of absorbent. Thus, the resistance introduced by the absorbent in the larger present day canisters is little different from that of the smaller canisters used when absorption was first introduced.

Moisture Content. The moisture content of soda lime, as has been mentioned previously, is a matter of considerable importance as far as effective absorption is concerned. Two types of soda lime are available, the wet or high moisture and the dry or low moisture. The low moisture lime is not suitable for anesthesia practice.²⁶ Neither sodium hydroxide nor calcium hydroxide forms a hydrate. The moisture in soda lime, therefore

is not present in any definite proportions. Sodium hydroxide is hygroscopic; calcium hydroxide is not. The water in soda lime is probably present as a thin film of sodium hydroxide solution on the surfaces of the particles of calcium hydroxide. Anhydrous soda lime exposed to a humid atmosphere absorbs some water. However, the quantity absorbed is not remarkable since the sodium hydroxide content is approximately 5 per cent. The moisture must be deliberately added to assure a high content. High moisture soda lime on the other hand loses water when exposed to dry atmosphere. The moisture content of soda lime, therefore, may be variable and depends to a large extent upon the water content of the atmosphere to which it is exposed. When the moisture content exceeds 20 per cent the mass assumes a soggy, moist appearance.²¹ The moisture is not visible when the content is less than 20 per cent. Neutralization becomes progressively more effective as the moisture content increases up to approximately ²¹ 20 per cent. Beyond this increasing the moisture content produces little or no significant advantage. From a clinical standpoint the neutralizing ability of soda lime containing 10, 15 and 20 per cent moisture is about the same.²⁶ Efficiency falls off when the moisture content falls below 10 per cent.²¹

U.S.P. Requirements. Soda lime is included in the U. S. Pharmacopoeia.²² The Latin name for the mixture is *calx sodica*. The U.S.P. specifications for soda lime are broad. In order to meet U.S.P. requirements the substance should be white and composed of sodium hydroxide, calcium hydroxide, and potassium hydroxide. The U.S.P. recognizes soda lime as a mixture of variable composition and specifies no fixed percentage of alkali. Ordinarily soda lime available on the American markets contain 5 per cent sodium hydroxide, approximately 1 per cent potassium hydroxide, calcium hydroxide and moisture. The specified moisture content of soda lime likewise is variable but should not be less than 14 per cent or exceed 19 per cent.

BARALYME

Mixtures of barium and calcium hydroxide, known as Baralyme, are also used to absorb

CO₂. Baralyme was introduced in 1939 by the Thomas Edison Company of New Jersey. Baralyme is composed of 20 per cent barium hydroxide and 80 per cent calcium hydroxide. The absorption efficiency of this mixture parallels that of soda lime. The preparation was first made available as compressed cylindrical tablets, $\frac{3}{16}$ inch in diameter. The granular form similar to granular soda lime is now available. The granular form absorbs CO₂ more efficiently than the pellets.²² The mass is of sufficient hardness to withstand handling and mechanical abuse in metallic canisters. Silica is not necessary to harden the particles. Barium hydroxide plays the role of activator in the same manner that sodium hydroxide does in soda lime. Barium carbonate, calcium carbonate and water are the products of the reaction. The heat evolved is quantitatively the same as that resulting from the neutralization of carbonic acid by soda lime. The moisture in Baralyme is chemically united with the barium hydroxide in the form of the octahydrate (Ba(OH)₂·8H₂O). This situation differs from that of soda lime in which the water is present as a film over the surface of the pores of the granule. The water content of Baralyme is less apt to vary when exposed to dry or humid atmospheres than soda lime because it is chemically bound. If Baralyme is heated above 150 C., however, the water of hydration is lost. The desiccated material is ineffective in absorbing carbon dioxide. Wetting the mixture with water produces a useless, doughy mass. At the time the mixture was first introduced as an absorbent, studies by Kilborn²⁴ and Adriani and Batten²⁵ indicated that Baralyme was equally as effective and in some respects superior to soda lime as a CO₂ absorbent. The soda lime specimens being compared with the Baralyme were those available in 1938. Considerable improvement has been made in soda lime since that time. Recently studies by the reviewer²⁶ and Elam and Brown²⁶ indicate that soda lime now available (Wilson and Malinckrodt) is a more effective absorbent than Baralyme under identical conditions of exposure to CO₂. This is not surprising since the activator, barium, is less active chemically than sodium. Besides, barium hydroxide is less soluble than that of sodium. Recently

traces of potassium hydroxide have been added to the mixture to improve its efficiency. The barium ion is toxic. The discarded Baralyme is a mixture of insoluble carbonates. However, if ingested barium carbonate reacts with the hydrochloric acid in the stomach to yield soluble barium chloride which yields the barium ion.

CANISTERS

The size and shape of the canister holding the absorbent is important. Little was known about the inner workings of the canister when the absorption technique was first introduced because controlled studies under clinical conditions were impossible. Significant data have been obtained in the laboratory using mechanical spirometers which simulate breathing as it is encountered during clinical anesthesia.^{7, 22, 26, 26} In this way the many variables encountered clinically are eliminated. One of the questions which arose in these studies was how much CO₂ should be introduced into the canister which would represent the average CO₂ output during anesthesia in an adult. Until recently little data have been available concerning CO₂ excretion during anesthesia. Most workers have assumed that the respiratory quotient during anesthesia to be 1. On this basis the CO₂ output of an adult would average 200 ml. per minute. Adriani and Rovenstine used this value in their studies.²² In order to clarify this point the reviewer and his associates determined the CO₂ excreted by collecting the expired gases in toto measuring the carbon dioxide content.²⁶ The output in 30 anesthetized adults ranged from 185 to 425 ml. per minute and averaged 210 ml. The output was somewhat greater for males than females. Carbon dioxide output does not fluctuate from moment to moment as is commonly believed but remains surprisingly constant once anesthesia has been established and a steady state is achieved. On the basis of these data, all tests were performed using 200 ml. per minute as the CO₂ output.

Certain basic information has been obtained in these laboratory studies.²⁶ The duration of inspiration and expiration appears to have no effect on the efficiency of absorption in either the to-and-fro or the circle filter. Absorption is as effective when the gases are

unhumidified as when they are humidified, provided the soda lime is of a high moisture content. The moisture must be incorporated in the absorbent. The position in which the canister is placed is immaterial provided the absorbent is tightly packed in the canister, so that channeling does not occur. Absorption is as effective in a horizontally placed canister as one arranged vertically. Absorption is equally as effective when the gases pass through the lime from below upwards through a vertically placed canister as from above downwards.²⁶ The absorption is equally as effective in canisters having bypass tubes in the center as those without such a tube, provided that channeling is avoided.

PATTERN OF ABSORPTION IN TO-AND-FRO CANISTERS

Waters by repeated clinical trials noted the optimal size of a to-and-fro canister was 8 × 13 cm.⁸ The reason for this became apparent from the laboratory studies of Adriani and Rovenstine.²² They noted that absorption was optimal when the air space between the soda lime granules and the tidal volume were equal. The bulkiness of soda lime is deceptive. Even though the absorbent appears to fill the canister the volume of air between the granules and within the pores of the granules is surprisingly large. The air space in a 8 × 13 cm. canister filled with 6 × 8 mesh soda lime varies between 375 and 425 ml. This air space corresponds closely to that of the tidal volume of an anesthetized patient breathing unassisted. Adriani and Rovenstine²² visualized the flow of gases in a canister by coating the granules with lead acetate and adding hydrogen sulphide to the ambient gases in the mechanical ventilator. The granules darken as the black lead sulphide forms on the surface, since hydrogen sulphide is an acidic gas. In the to-and-fro unit, the granules at the inlet of the canister darkened first. Later those at the outlet. As the absorption proceeded, the granules along the side darkened. The granules along the side darkened more than those in the core. The ambient gases follow the path of least resistance. They sweep along the sides of the canister into the bag. The granules in the core of the canister offer more resistance

than those along the sides. The granules facing the screens at the mask and bag are darkened completely. As absorption proceeds and the charge is exhausted the entire surface of the granules at the inlet and the outlet darken. The granules in the center are only partly discolored. At terminal exhaustion a rhomboid shaped area composed of partially discolored granules remains in the core in the distal outlet or half of the canister. The granules on the periphery of this area are discolored on the surface facing the sides and white on the surface facing the core. In confirmatory studies the absorbent taken from various areas in the canister were analyzed for CO₂ content. Carbon dioxide content is highest in the areas of maximum discoloration.²²

PATTERN OF ABSORPTION IN THE CIRCLE FILTER

The pattern of absorption in the circle filter differs somewhat from that of the to-and-fro. Discoloration is absent at the points of contact of the contiguous granules.²² As is the case of the to-and-fro, the gases sweep along the sides preferentially. Ultimately the granules are uniformly darkened similar to the to-and-fro. The rhomboid shaped area or blind spot is similar to that found in the to-and-fro in the terminal end of the canister. Chemical analysis of samples of the absorbent removed from various parts of the canister reveal the pattern of exhaustion being similar to that of the to-and-fro. The greatest concentration of carbon dioxide is in the granules at the inlet and along the sides. The concentration decreases progressively towards the outlet. In large canisters the absorbent at the downstream portion of the canister is less than 50 per cent exhausted at the time carbon dioxide appears in detectable amounts at the outlet. The absorbent is utilized to its fullest capacity using divided canisters.

SHAPES OF CANISTERS

Globular, oval, conical, oblong and other shape canisters may be used to absorb CO₂ with apparently the same efficiency, provided the tidal volume of the absorbent is equal to the air space in the canister.²⁸ Differences

of clinical importance may be due to resistance of the passage of gases rather than to absorption and time efficiency. Canisters are constructed of metal, usually brass or steel. Recently plastic canisters have become popular because of transparency. Metals possess an advantage over certain plastics because they withstand contact with the alkali. Besides they conduct heat better than most plastics. This helps dissipate heat resulting from the chemical reaction. This is important particularly in the to-and-fro unit.

Several schools of thought exist concerning total elimination of CO₂. One school says that total removal should be achieved but cannot be achieved and, therefore, the absorption technique should be abandoned. These individuals are in error. Another believes that traces of CO₂ do no harm and continue to use to-and-fro and circle filters which may not be performing at top capacity. Another concludes that CO₂ must be and can be completely removed by absorption with alkali. Those who have studied the problem carefully subscribe to this point of view.^{26, 26} Actually complete, absolute removal of CO₂ does not occur at any time. A trace passes through at all times.²⁶ However, this trace is not detectable by ordinary methods of analysis and is insignificant. The CO₂ concentration is far less than is found in the atmosphere. The fact that some CO₂ comes through is not difficult to understand. The distance between the granules of absorbent is considerable compared to the size of the molecules of CO₂. Thus, some molecules of CO₂ are able to slip through without ever coming into contact with the soda lime granules. Then, also CO₂ is not highly soluble and chemically active. Many of the molecules which do come into contact with the absorbent may not be neutralized. Gradually as the alkali on the surface of the granules in various parts is neutralized, more molecules of CO₂ fail to react and pass on through. The ensuing concentration gradually increases and soon reaches a detectable level. The concentration at this point may still be less than is ordinarily found in the atmosphere and be of no clinical significance. This unabsorbed CO₂ is recirculated. The concentration continues to increase and finally reaches a point at which it is no

longer tolerable to most patients. The amount of CO_2 which can be recirculated in this manner differs immensely from patient to patient. In most patients, the effects of hypercapnia become noticeable when 0.5 per cent filters into the mask.²⁶ The use of two canisters in series as suggested by Adriani²⁶ or the divided canister as suggested by Elam and Brown²⁶ obviates this difficulty in the circle system. The "spill over" of CO_2 from the first canister is absorbed by the second. In the divided canister the lower section absorbs the "spill over." Carbon dioxide, in detectable quantities, need never appear in the filtered gases. Complete removal is impossible to achieve in the to-and-fro filter. More is said of this later.

AIR SPACE IN CANISTERS

The importance of the air space in a canister has been emphasized in the preceding paragraphs. The total air space is composed of the space between the granules or intergranular space and that within the granules or intragranular space. Absorbents have varying degrees of porosity. The total air space of a given quantity of absorbent may be computed by specific gravity²⁶ or by actually displacing the air with water,²² cyclohexane, or other fluid. The intergranular air space varies with the number of granules in a given volume. The smaller the mesh of soda lime the greater the number of granules and the total weight of absorbent and the less the air space. The pore air space varies with the moisture content. High moisture content limes have less than low moisture since water occupies the pores. It is doubtful that a true measure of air space in the pores is obtainable. As absorption proceeds, the pore space decreases due to the fact that carbonate occupies the space. The total air space is anywhere from 40 to 60 per cent of the total volume of a canister, depending upon the particular absorbent examined. The total air space is less for Baralyme than for soda lime. The pore air space varies between 2-3 ml. per gram of either Baralyme or soda lime.²⁴

The question naturally arises how large should a canister be in the circle system? The canister may be as large as one chooses to have it provided the air space accommodated

by the absorbent is greater than the maximum anticipated tidal volume. When the divided canister is used or two canisters are connected in series, a total air space of twice the maximum anticipated tidal volume to be accommodated during clinical use is a reasonable figure.

REGENERATION OF ACTIVITY

Early in the use of CO_2 absorption a phenomenon referred to as "peaking" was reported.²² The absorption efficiency would fall off very quickly after several hours use of a charge of soda lime. When the charge was set aside and allowed to remain idle for several hours and then used again under the same conditions, absorption proceeded nearly as efficiently as before but for a shorter period of time. After a number of such periods of efficient absorption with intervening rest periods, terminal exhaustion occurred. In other words the soda lime appeared to be reactivated with rest. This reactivation is explained by the fact that sodium hydroxide, which is more soluble and more active chemically than calcium hydroxide, combines preferentially with CO_2 to form sodium carbonate.²⁵ Sodium carbonate, because it is soluble, dissolves in the moisture in the granule. It, thus, can permeate into the granule and react with the less active and less soluble un-neutralized calcium hydroxide to form calcium carbonate, which is insoluble, and sodium hydroxide. The moisture in a soda lime granule forms a film on the surface within the porous mass of calcium hydroxide composing the granule. This moisture is actually a solution of both hydroxides. Since sodium hydroxide is more soluble than calcium hydroxide, it predominates in the water film. Upon exhaustion the film predominately contains sodium carbonate. The reaction is not reversible, since calcium carbonate is insoluble. The regenerated sodium hydroxide imparts the renewed activity to the absorbent. This regeneration may be demonstrated in the laboratory by placing the exhausted soda lime in absolute alcohol.²⁷ Sodium hydroxide is soluble in alcohol while the other ingredients in soda lime are not. Specimens before resting show no sodium hydroxide while those after resting do. Calcium hydroxide also absorbs

CO₂ directly to form calcium carbonate without this intermediary reaction but this direct reaction is less prominent. Heidbrink²⁰ was one of the first to recognize the need for these periods of "rest" and equipped his apparatus with dual canisters with selective valves to permit alternation of charges. One charge could be bypassed while the other was in use. This "peaking" is seldom seen in present day practice due to recent improvements in soda lime.²⁶ The interaction between the soluble carbonates and calcium hydroxide still occurs but keeps pace with absorption. The alternation of canisters no longer appears to be necessary. The differences between the older soda limes and those in present day use are (1) less silica is now incorporated in the lime. This reduces hardness and, thus, the permeation of the soluble constituents into the granules is facilitated and the interaction of carbonates and hydroxides occurs more readily. (2) The moisture content is better controlled, more uniform and higher. Moisture is necessary for the interaction to occur and maintain the pace with absorption. (3) Small quantities of potassium hydroxide are now added to soda lime. This enhances the activity of the absorbent. Adriani and Batten²² and Kilborne²⁴ reported no "peaking" with Baralyme. Both barium and calcium carbonates, as has been mentioned previously, are insoluble and, therefore, cannot interact. Consequently no regeneration of activity occurs with Baralyme as it does in the case of soda lime.

TEMPERATURES AND ABSORPTION

The temperature of the gases entering the canister does not appreciably influence the absorption efficiency from a clinical standpoint.²⁶ Canisters ventilated with air containing 2 per cent CO₂ at 0 C., 28 C. and 40 C. absorbed effectively in each case.

The reaction of absorption is exothermic. Consequently canisters warm up when in use. The heat which is evolved, however, is for the most part, but not entirely, derived from the reaction of neutralization. Another possible source of heat is the heat of solution. The amount evolved from this source, however, is negligible when using present day absorbents, because the sodium hydroxide content is low and moisture content is high. Solution of

the hydroxide has already occurred. Absorbents which contain high percentages of sodium hydroxide and low moisture release heat as they absorb water due to the hygroscopic properties of sodium hydroxide. Heat is also evolved when the moisture condenses in the breathing bag and tubings. This moisture has a dual origin. Part of it comes from the patient's lungs and some results from condensation of water vapor liberated by the reaction of neutralization.

The temperature of the reacting absorbent in the heart of a to-and-fro canister at times may exceed 60 C.²² This, since the canister is so close to the face piece, frequently causes the inspired air to be warmed above body temperature. The temperature in the mask may be anywhere from 39 to 42 C.²² Temperatures in all portions of a canister drop as soon as terminal exhaustion occurs. A cool canister usually indicates the absence of chemical activity and inadequate absorption. However, a low CO₂ output may not liberate sufficient heat to warm the canister. Pattern of temperature ranges similar to the to-and-fro are noted in the circle filter. The average range, however, is approximately 5 to 10 degrees less than in the to-and-fro. This is understandable since the opportunity for loss of heat by conduction, convection and radiation is greater in the circle filter than to-and-fro filters. The temperature of the jacket of a circle filter offers little clue as to the temperature of the reacting absorbent in the interior. Palpation of the canister yields more information in the case of the to-and-fro than in the circle.

SODA LIME CONTAINING INDICATORS

Soda lime is impregnated with dyes which change color when the hydroxides are neutralized and converted to carbonates. These dyes, referred to as indicators, are acids which form salts with bases.²⁵ Ethyl violet is a colorless base impregnated in certain brands of soda lime. The reacts with carbonic acid to form the soluble carbonate which is purple. When all the soda lime is converted to sodium and calcium carbonate, the purple color appears. Clayton yellow is also used as an indicator for other soda limes. The basic form is red; the acid form is yellow. The soda

lime granules impregnated with the dye appear pink when fresh; when exhausted they are yellow. To be useful for CO_2 absorption, the color change of an indicator must occur at a high pH range.

Soda lime with indicators was received with enthusiasm when the idea was first conceived. After extensive clinical trials it was found that the physiological end-point, that is, the point at which hypercarbia becomes intolerable to most patients, did not coincide with the chemical end point, the point at which the color change occurred.²⁸ Usually, signs of hypercarbia appear before the color change. In some filters, after a charge of absorbent has been in use for some time, the granules along the sides of a canister change color while those in the core have not changed, since the gases sweep along the sides more easily than through the center. Thus, the color change along the sides is not necessarily an index of the state of the absorbent throughout the entire canister. Besides CO_2 may be leaking through due to channeling without any color change in the granules facing the canister. Also a color change may occur and disappear after the charge stands. This reversal of color change is due to the regeneration and reformation of traces of sodium hydroxide. This change may occur when the absorbent is exhausted sufficiently to be of no further value clinically but still contains enough alkali to cause enough regeneration to cause color transformation. Thus, up to now indicators have been of little service.²⁸

However, indicators are of value in the circle system employing the divided canister or canisters in series. The absorbent is used until the color change occurs in the first half of the divided canister or the first of two in series. This is removed and replaced by the partially exhausted remaining portion and a fresh charge is placed in the position previously occupied by the partially used charge. It must be emphasized that the only final assurance of complete removal of carbon dioxide is to use a method of detecting the gas in the outlet of the filter.

COMPLETENESS OF EXHAUSTION OF ALKALI

Utilization of a charge of soda lime to the point of complete neutralization of its con-

tained alkali seldom occurs. The percentage utilized varies widely under different clinical conditions, with the type of absorbent and the design of the canister. Some of the alkali in the heart of the granules remains unused at the point of clinical terminal exhaustion when intolerable quantities of CO_2 are returned to the mask. Since soda lime is a mixture of two hydroxides together with water the theoretical capacity of the mixture for CO_2 will vary with the composition. Besides the ease with which the gas penetrates into and neutralizes the alkali in the heart of the granule may vary. The porosity is also an important factor. This varies as absorption proceeds because the pores become clogged with water or are occluded by dust, the expanding carbonate or changes in water content. In a charge no longer effective for clinical use the CO_2 content of the granules varies in different parts of the canister. It is greater in the granules at the inlet and along the sides. The utilization of the theoretical capacity of soda lime may be as low as 35 per cent in one part of the canister and as high as 85 per cent in others. The average of all granules is approximately 50 per cent in filters with single canisters and 70 per cent in those in which the canister is divided or two canisters are used in series.²⁹ The object of the technique is to obtain a unit which functions satisfactorily, as a whole, and removes carbon dioxide completely. Some granules in one part are bound to be neutralized more than others at the point of terminal exhaustion because the distribution and the concentration of carbon dioxide containing gas is not uniform in all parts of the canister.

CARBON DIOXIDE DETECTORS

Devices for detecting and determining quantitatively the concentration of carbon dioxide in the effluent gases have been introduced from time to time,²⁹ but thus far none has proved practical. These devices employ chemical methods of detection of carbon dioxide. The underlying principle in most of these detectors is the determination of the volume of gas necessary to neutralize a dilute solution of alkali containing an indicator. The gas is drawn from an inhaler with a calibrated bulb and bubbled through the

alkali. The percentage of carbon dioxide present is determined by the number of squeezes or bulbfuls necessary to offset a color change. Most of these devices have proved to be cumbersome, or inaccurate. The alkaline dust coats the tubing and finds its way into the solution in the detector and renders the method inaccurate.⁴⁰ Strips of paper impregnated with indicators, such as phenol red or bromthymol blue, have been used at the exit of the canister. They too are not satisfactory because in due time minute traces of CO₂ which unavoidably leak through convert the dye to the basic form. The Liston-Becker Infra-Red analyzer is extremely sensitive but is cumbersome and impractical for ordinary use in an operating room.

CHANNELING

A phenomenon referred to as channeling may be responsible for a considerable reduction in efficiency of absorption and ultimately leads to hypercarbia and a waste of soda lime. This has been emphasized by Brown and Elam.²⁶ Unless the absorbent is packed tightly and uniformly the gases follow the path of least resistance and create channels directly from the inlet to the outlet of the canister. Thus, they bypass the bulk of the granules of absorbent and incomplete neutralization occurs. These channels may be visualized by using hydrogen sulphide and lead acetate coated granules mentioned before or soda lime with indicators. Streaks of partially darkened granules radiating throughout the mass of absorbent indicate that channeling has occurred. The side of the canister should be tapped while it is being filled to assure uniform distribution of absorbent. A screen on top of the canister which tightly fixes the mass of granules assures no movement. Channeling may also be caused by faulty canister design. Channeling is prone to occur in canisters having bypass tubes in the center. Disks referred to as baffles are sometimes placed at the inlet or outlet of canisters to direct the gases in a more uniform fashion throughout the charge of absorbent. A channel is often established in a to-and-fro unit along the top of a canister, particularly after it has been in use some time, when it is held horizontally or partially in-

clined. The constant handling of canisters causes fragmentation and shifting of the granules, particularly if not tightly packed. The shifting leaves a void along the top which results in a channel from inlet to outlet.

"CAKING"

The phenomenon referred to as "caking" occurred frequently in the early days of CO₂ absorption. The absorbent became matted together in a hard solid mass. This was due to the high sodium hydroxide content, which because of its hygroscopic properties absorbed water. The granules became adherent and matted together as they became water-logged. The mass formed a cake when the hydroxides which are soft become converted to carbonates which are hard. A high silica content contributed further to the hardening process. Absorbents in present day use are devoid of this objectionable property. "Caking" may occur when canisters of faulty design are used which permit accumulation of condensed water vapor in pools at the bottom so that the absorbent becomes water-soaked. The processes of "caking" is identical to the hardening of plaster spread on a wall. Calcium hydroxide in fresh plaster is gradually converted to calcium carbonate as CO₂ is absorbed from the air.

OBJECTIONS TO THE TO-AND-FRO CANISTER

The statement that efficiency is optimal when the air space equals tidal volume is applicable for only short periods of time in a to-and-fro canister, after which efficiency gradually decreases as the alkali is neutralized. The question then is how long does this efficient absorption last. For those who believe that CO₂ must be completely removed, this efficiency is seldom more than 15 minutes. After this time traces of carbon dioxide trickle through. However, the concentration which ultimately causes serious hypercarbia requires 4 or 5 hours to build up. The dead space in the to-and-fro canister increases progressively inward from the screen in the front part of the canister towards the bag end.^{7,22} This situation is most pronounced when the tidal volume of the patient is less than that of the air space in the canister.⁴² The soda lime at

the inlet becomes exhausted while that at the outlet remains active. The intergranular and pore air space at the inlet is exhausted after a time and becomes dead space since the gases are rebreathed without being freed of CO_2 . Such a progressive extension of dead space occurs during shallow breathing, during anesthesia for small adults or in children when large canisters are used. Smaller canisters such as 6×7 and 7×12 cm. should be employed in subjects with low tidal volume for more efficient absorption. This problem is not present in the circle filter, since the pattern of absorption is different and most tidal volumes do not exceed canister air space.

STABILITY OF ANESTHETICS IN THE PRESENCE OF SODA LIME

The majority of inhalational anesthetics are stable in the presence of soda lime.²⁸ Trichlorethylene is a notable exception.⁴¹ All the ethers, cyclopropane, ethylene and nitrous oxide undergo no change. Ethyl chloride is an ester of ethyl alcohol and hydrochloric acid and may, therefore, be hydrolyzed into these products by the alkali. The hydrochloric acid would, of course, be absorbed by the alkali but the alcohol remains unchanged. The rate of hydrolysis varies. Halothane undergoes no change. Trichlorethylene undergoes chemical changes when in contact with warm alkali. Some oxidation to phosgene occurs. However, the more dangerous product is dichloroacetylene which is neurotoxic and explosive. Trichlorethylene does not cause any deleterious effect immediately upon contact with the alkali.⁴¹ Instead, the compound is absorbed by the granules and the dichloroacetylene forms gradually. The patient exhaling the trichlorethylene does not necessarily suffer the ill-effects. The patient who is anesthetized later who inhales the compound experiences the difficulties.

SUMMARY

Carbon dioxide is eliminated from inhalers either by exhaling it into the outside atmosphere through a valve or by absorbing it with chemicals. Quantitative elimination of the gas being excreted is not accomplished in the washout technique, unless the total quantity

of gas being expelled from the inhaler is equal to or greater than the minute volume exchange of the patient at a particular moment. The flow rate of any gas into any inhaler having the same oxygen content as atmospheric air must be equal to or be greater than the minute volume exchange of the subject breathing from the inhaler. Flow rates less than the minute volume exchange not only lead to an accumulation of CO_2 in the system but also to inspired oxygen tensions below the physiologic level. In other words, the volume supplied must be equal to the volume inspired; the volume forced outward must equal the volume expired. Neither sub-oxygenation nor CO_2 accumulation are problems in systems supplying and ejecting gases on demand. When flow rates less than the minute volume exchange are used CO_2 must be absorbed by chemicals and the mixture must be enriched with oxygen.

Alkalies are used for absorbing CO_2 from mixtures of gases and vapors. Mixtures of the hydroxides of sodium, potassium, calcium and barium are the most suitable. Ion exchange resins, silica gel, aluminates, zincates, organic amines have been tried but not been found practical.

Of the two types of closed inhalers, the circle system is almost universally used. The effectiveness of CO_2 absorption using soda lime or Baralyme in either system depends upon the air space in a loaded canister. In the to-and-fro system optimum absorption occurs when tidal volume equals the air space between the granules. Complete removal is virtually impossible in the to-and-fro unit due to the progressive increase in dead space as the absorbent is neutralized. Effective absorption can only be expected for short periods. The most efficient absorption is obtained when tidal volume equals air space in the canister. In the circle system the air space must be equal to or greater than the tidal exchange of the subject. Carbon dioxide begins to pass through long before all the alkali in a charge is neutralized. The absorbent at the inlet becomes exhausted before that at the outlet. The indicator in this portion shows a well-defined color change. The partially exhausted downstream portion is still capable of absorbing CO_2 and shows no color change.

The alkali of a charge may be utilized to the fullest extent by using divided canisters. The exhausted half at the upstream portion is discarded and replaced by the partially used portion at the outlet section. Fresh absorbent is placed in the downstream section. Using this arrangement CO₂ is completely removed at all times.

Moisture is essential for effective neutralization. This must be incorporated in the granules of the soda lime. The moisture contained in the ambient gases plays little role in the neutralization. The position of the canister and the direction of flow of gases are of no particular importance as far as absorption is concerned.

A simple, accurate, foolproof method of determining the percentage of CO₂ in gases issuing from the canister remains to be devised. Indicating dyes added to the absorbent cannot be relied upon in determining when absorption is inadequate. The color of the indicator may remain unchanged even though intolerable concentrations of CO₂ are passing through the absorbent.

The chemical absorption technique, if correctly managed, permits adequate removal of CO₂. The problems of hypercarbia are mainly due to hypoventilation and cannot be corrected by the use of high flow rates, elaborate canisters or complex valves.

REFERENCES

- Adriani, J.: Measurements performed for this symposium, unpublished.
- Foregger, R. Jr.: Classification and performance of respiratory valves, *ANESTHESIOLOGY* 20: 296, 1959.
- Swartz, C. H., Adriani, J., and Mib, A.: Semi-closed inhalors: studies of carbon dioxide tensions during various conditions of use, *ANESTHESIOLOGY* 14: 437, 1953.
- Miles, G., Martin, N. T., and Adriani, J.: Factors influencing elimination of nitrogen using semi-closed inhalors, *ANESTHESIOLOGY* 17: 213, 1956.
- Reuben, H.: Concerning concentrations of inhaled gases in semi-closed anesthesia systems, *ANESTHESIOLOGY* 14: 449, 1953.
- Macintosh, W., and Mushin, W.: *Physics for the Anesthetist*. London, Blackwell, 1959, pp. 274-275.
- Elam, J. O., and Brown, E. S.: Evaluation of partial rebreathing systems, *ANESTHESIOLOGY* 17: 116, 1956.
- Waters, R. M.: Advantages and technique of carbon dioxide filtration with inhalation anesthesia, *Anesth. & Analg.* 5: 160, 1926.
- Waters, R. M.: Absorption of carbon dioxide from anesthetic atmospheres, *Proc. Royal Soc. Med.* 30: 11, 1936.
- Duncum, B. M.: *Development of Inhalation Anesthesia*. London, Oxford University Press, 1947, Ch. 10.
- Keyes, T. E.: *The History of Surgical Anesthesia*. New York, Schumans, 1945.
- Snow, John: On narcotism by inhalation of vapours, *London M. Gaz. n.s.* 12: 622, 1851.
- Benedict, F. C., and Tower, E.: Calcium and sodium hydrate for carbon dioxide absorption, *J. Amer. Chem. Soc.* 21: 396, 1899, also *Amer. J. Physiol.* 24: 345, 1909.
- Jackson, D. E.: New method for production of general analgesia and anaesthesia with a description of apparatus used; *J. Lab. & Clin. Med.* 1: 1, 1915.
- Brown, E. W.: Value of high oxygen; *U. S. Naval Bull.* 28: 523, July 1930.
- Brindley, G., and Foregger, R.: Experiments with fused sodium peroxide, *Trans. Amer. Chem. Soc.*, May, 1906, pp. 290-295.
- Rovenstine, E. A.: Carbon dioxide absorption method for inhalation anesthesia, 34: 356, 1936.
- Wilson, R. E.: Preparation of soda lime, *J. Indust. & Eng. Chem.* 12: 1000, 1920.
- Sword, B. C.: Closed circle method of administration of gas anesthesia, *Anesth. & Analg.* 9: 198, 1930.
- Heidbrink, J. A., and Keyes, T. E.: Development of anesthesia, *ANESTHESIOLOGY* 4: 417, 1943.
- Connell, K.: Carbon dioxide absorption, *Anesth. & Analg.* 12: 161, 1933.
- (a) Adriani, J., and Rovenstine, E. A.: Experimental study of carbon dioxide absorbers for anesthesia, *ANESTHESIOLOGY* 2: 1, 1941.
(b) Adriani, J., and Byrd, M. L.: Canister, *ANESTHESIOLOGY* 2: 450, 1941.
- Waters, R. M.: Toxic effects of carbon dioxide, *New Orleans Med. & Surg. J.* 90: 219, 1937.
- Henderson, Y.: Resuscitation with carbon dioxide, *Science* 83: 399, 1936.
- Conroy, W. A., and SeEVERS, M. H.: Studies in carbon dioxide absorption, *ANESTHESIOLOGY* 4: 160, 1943.
- (a) Brown, E. S., and Elam, J. O.: Carbon dioxide homeostasis during anesthesia; total sampling for determination of dead space alveolar ventilation and carbon dioxide output, *ANESTHESIOLOGY* 16: 886, 1955.
(b) Brown, E. S.: Performance of absorbents: continuous flow, *ANESTHESIOLOGY* 20: 41, 1959.

- (c) Elam, J. O., and Brown, E. S.: Carbon dioxide homeostasis during anesthesia; ventilation and carbon dioxide elimination, *ANESTHESIOLOGY* 17: 116, 1956.
- (d) Brown, E. S.: Activity and surface area of fresh soda lime; *ANESTHESIOLOGY* 19: 208, 1958.
- (e) Brown, E. S.: Voids, pores and total air space in carbon dioxide absorbents, *ANESTHESIOLOGY* 19: 1, 1958.
- (f) Brown, E. S., and Elam, J. O.: Practical aspects of carbon dioxide absorption, *New York J. Med.* 55: 3436, 1955.
- (g) Brown, E. E., and others: Performance of absorbents: effects of moisture, *ANESTHESIOLOGY* 20: 613, 1959.
- (h) Ten Pas, R., Brown, E. E., and Elam, J. O.: Circle versus the to-and-fro, *ANESTHESIOLOGY* 19: 231, 1958.
- (i) Elam, J. O.: Channeling and overpacking in carbon dioxide absorbers, *ANESTHESIOLOGY* 19: 403, 1958.
- (j) Peterson, P. N., and Elam, J. O.: Elimination of carbon dioxide, *Anesth. & Analg.* 37: 91, 1958.
27. Beecher, H. K., and Todd, D. P.: Deaths associated with anesthesia. Springfield, Illinois, Charles C Thomas, Publisher, 1954.
28. Adriani, J.: Chemistry of Anesthesia. Springfield, Illinois, Charles C Thomas, Publisher, 1946, Ch. 4.
29. (a) Derrick, W. S., and Smart, R. C.: Carbon dioxide absorption properties of monoethanolamine, *ANESTHESIOLOGY* 18: 551, 1957.
- (b) Smart, R. C., and Derrick, W. S.: Carbon dioxide absorption of ion exchange resins, *ANESTHESIOLOGY* 18: 216, 1957.
30. Adriani, J.: Unpublished experiments on use of zincates and aluminates of sodium.
31. Adriani, J.: Effect of varying moisture content of soda lime upon efficiency of carbon dioxide absorption, *ANESTHESIOLOGY* 6: 103, 1941.
32. Pharmacopoeia of the United States XV, Easton, Pa., Mack Publishing Co., 19 5, p. 634.
33. Nelson, T. F., Chase, H. F., and Gibbon, J. H.: Factors influencing carbon dioxide absorption during anesthesia, *ANESTHESIOLOGY* 19: 75, 1958.
34. Kilborn, M. G.: Preliminary clinical report on new carbon dioxide absorbent Baralyte, *ANESTHESIOLOGY* 2: 621, 1941.
35. Adriani, J., and Batten, D. H.: Efficiency of mixtures of barium and calcium hydroxide to absorb carbon dioxide, *ANESTHESIOLOGY* 3: 1, 1942.
36. Miles, G., and Adriani, J.: Carbon dioxide absorption: closer look, *Anesth. & Analg.* 38: 293, 1950.
37. Foregger, R.: Regeneration of soda lime following absorption of carbon dioxide, *ANESTHESIOLOGY* 9: 15, 1948.
38. Adriani, J.: Carbon dioxide in soda lime containing indicators, *ANESTHESIOLOGY* 5: 45, 1944.
39. Dornette, W., and Brechner, V. L.: Instrumentation in Anesthesiology. Philadelphia, Lea & Febiger, 1959, p. 161.
40. Draper, W. B., and Longwell, B. B.: Proposed device which is capable of continually indicating approximate percentages of carbon dioxide in stream of flowing gases, *Colorado Med.* 32: 899, 1935.
41. Fabian, L. W., Stephen, C. R., and Bourgois-Gavardin, M.: Place of trichlorethylene in obstetrical and anesthesia practice, *South. M. J.* 49: 808, 1956.
42. Adriani, J., and Griggs, T.: Rebreathing in pediatric anesthesia, *ANESTHESIOLOGY* 14: 337, 1953.