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THE EFFICIENCY OF MIXTURES OF BARIUM AND CALCIUM HYDROXIDES IN THE ABSORPTION OF CARBON DIOXIDE IN REBREATHING APPLIANCES *

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THE removal of carbon dioxide from rebreathed mixtures at present can be accomplished only by chemical methods. The only satisfactory absorbents are the hydroxides of the alkali metals—potassium, sodium, lithium—and of the alkaline earth metals—barium, strontium, calcium and magnesium. The process of absorption is a reaction of neutralization since carbon dioxide forms carbonic acid which is neutralized by these alkalis to yield water and the respective carbonate. The heat which is always evolved in the reaction is known as the heat of neutralization. The heat, except for variations due to the degree of ionization of the various acids and alkalis and other minor variable factors, is a constant value and amounts to 13,700 calories per gram molecule of water formed. The hydroxides of the alkali metals are more active chemically than those of the alkaline earth metals. Potassium is more active than sodium and sodium is more active than lithium. They are far more soluble than the alkaline earth hydroxides, and the carbonates which they form are likewise more soluble. Although potassium and sodium hydroxide are active and absorb acid substances more effectively, their use is not practical in clinical anesthesia because of their highly caustic nature. In addition, they are highly hygroscopic and form objectionable solutions from the moisture which they readily acquire from atmospheric air. In rebreathing units the moisture from the exhaled air is absorbed in a similar manner. The heat of solution of these alkalis is high, and this heat, coupled with the heat of neutrali-

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zation, results in excessively high temperatures within the system. Mixtures of alkali metal hydroxides with the alkaline earth hydroxides have been found more practical as the latter are less caustic and comparatively insoluble. From the standpoint of cheapness, mixtures of sodium and calcium hydroxides, known as soda lime, have been found most practical and are used clinically. Since it was first introduced as an absorbent in inhalation therapy, soda lime has undergone many changes. In order to decrease the tendency of deliquescence and to prevent excess heating of the sodium hydroxide, its proportion was reduced to as low a value as 5 per cent. The activity, of course, is reduced, but even with this low proportion of sodium hydroxide there is sufficient activity for clinical use. The mass which forms is soft and easily crumbles and produces objectionable alkaline dust. To avoid this, silica is added to impart hardness to the mass. The addition of too much silica reduces activity because, first, this silica is inert, and, secondly, the hardness prevents penetration of the reacting substances into the heart of the granule and inhibits the chemical reaction. A certain amount of moisture must be added, too, to facilitate the formation of the carbonic acid from the carbon dioxide to insure rapid absorption. Since the absorption is purely a surface phenomenon, the mass is formed into porous granules to enlarge the surface and allow penetration. The granules can be neither too small, which would add excessive resistance and favor "caking," nor too large, so as to expose a minimum surface for the unit weight of the particle.

Although highly satisfactory after these elaborate preparations are used to make it effective, soda lime is without certain desirable features. The required bulk for efficient absorption necessitates the use of large, cumbersome canisters. The precautions to insure its hardness have not entirely eliminated caking and dust formation from fragmentation of the granules. In those units where the canister is close to the mask this caustic dust, as well as the heat of reaction, is an objectionable feature. A more efficient absorbent with less bulk, free from dust and heat, would be desirable.

Recently, mixtures containing barium and calcium hydroxides have been tried for absorption and the preliminary trials offer considerable promise of their being effective. Barium hydroxide is less active chemically than sodium, but more active than calcium hydroxide. Likewise, it is less soluble than sodium, but more soluble than calcium hydroxide. The carbonate of barium is more soluble than that of calcium, though both may be considered insoluble when compared with sodium and potassium carbonates. Barium hydroxide may exist as a hydrate— $\text{Ba}(\text{OH})_2 \cdot 8 \text{H}_2\text{O}$. The hydrate has been found to be an effective absorbing agent when mixed with $\text{Ca}(\text{OH})_2$ in a ratio of 20/80.* This mixture is compressed into hard pellets 3/16 inch in diameter, of poro-

* Marketed as BARALYME by Thomas A. Edison, Inc., Medical Gas Division, Bloomfield, New Jersey.

sity suitable for the efficient absorption of CO_2 . The eight waters of crystallization present in the $\text{Ba}(\text{OH})_2$ serve to fuse the mixture into a homogeneous mass which will hold its shape and form under varying conditions of heat and moisture. The mass consists solely of the two alkalis and their waters of crystallization. No silica or other substance is required or added to impart hardness.

Although laboratory tests show that when exposed to carbon dioxide these pellets absorb the gas and the entire mass is converted into carbonates in due time, the only valuable and reliable data regarding the practical value of such a substance should be obtained under clinical conditions. However, this particular subject is difficult to study clinically for several reasons. A charge of absorbent lasts many hours over the usual duration of even lengthy operations. The output of carbon dioxide and tidal volumes not only vary from one patient to another but even from time to time in the same patient during clinical anesthesia. In view of such varying conditions, it is difficult to obtain satisfactory comparative data during clinical investigation. It is unfortunate that, in order to obviate these objections and still obtain data for comparative purposes, laboratory studies are essential. Adriani and Rovenstine (1) have devised a technic for studying absorbents in the laboratory in such a manner that their results can be applied clinically. A spirometer was constructed to simulate human respiration, with complete control of inspiration, expiration, respiratory pause, humidity, CO_2 output and temperature of incoming air. Studies have been made with this same technic comparing the barium lime mixture and standard soda lime. The temperature of the chemical reaction was noted also by placing thermometers in different portions of the canister in the manner described by Adriani and Rovenstine. Cylindrical canisters 8×13 cm. were charged with 500–520 Gm. of barium lime absorbent prepared in pellet form. They were aerated in a "to and fro" manner using a tidal volume of 500 cc., a respiratory rate of 20 per minute, in which the length of inspiration was 1.3 second, expiration, 1.0 second, and expiratory pause .66 second. A carbon dioxide output was constantly maintained at 200 cc. per minute, the humidity at 100 per cent, and the temperature of air entering the canister at 28 C. Samples of air withdrawn from the mouth of the canister both during inspiration and expiration at thirty minute intervals were analyzed for carbon dioxide content to determine the efficiency of absorption from time to time. These were analyzed on the manometric Van Slyke apparatus by absorbing the carbon dioxide with 0.1 N sodium hydroxide, expelling the air and subsequently reliberating the gas with 1.0 N hydrochloric acid in the extraction chamber, and again reabsorbing with alkali. Under these conditions it was found that effective absorption was maintained constantly for approximately seven hours (table 1). Under identical conditions, a charge of 4×8 mesh soda lime of 520 Gm. absorbed effectively for five and one-half hours. The exhaus-

TABLE 1

	1st hour	2nd hour	3rd hour	4th hour	5th hour	6th hour	7th hour	8th hour
Barium lime	.09%	.09%	0.1%	0.15%	0.25%	0.5%	.7%	.9%
Soda lime	.07%	.09%	.20%	.5%	.7%	Rest Period	—	—

Carbon dioxide in vols. % contained in the outgoing air of the canister. The two absorbents are compared under identical conditions. The samples were taken at the end of the indicated hour.

tion of soda lime after intervals with subsequent revival of activity following two or three periods of rest, as observed by Adriani and Byrd (2), was seen once more. This regeneration of activity is presumably due to the interaction of sodium carbonate which forms preferentially from the more active sodium hydroxide with the less active calcium hydroxide to form calcium carbonate and regenerate sodium hydroxide. The continued effective use of the barium lime mixture must be due to the higher proportion of the active barium hydroxide as compared to the percentage of activator, sodium hydroxide, in soda lime. The interaction between barium carbonate and calcium hydroxide, if it occurs, does so very slowly because of the insolubility of barium carbonate (.024 Gm. per liter H_2O at 25 C.). Calcium carbonate is less soluble than barium carbonate. Whatever the degree of this interaction may be, it is probably of no practical significance in the regeneration of any activity of the barium lime mixture. The temperature from reacting barium lime is lower than but does not vary radically from that of soda lime (table 2). On the thermometer in the front

TABLE 2

	1st hr.			2nd hr.			3rd hr.			4th hr.			5th hr.			6th hr.		
	F	M	E	F	M	E	F	M	E	F	M	E	F	M	E	F	M	E
Barium lime	64	62	47	62	68	51	60	70	55	54	66	64	48	50	58	45	58	63
Soda lime	65	56	42	67	63	50	66	68	58	55	71	62	50	71	65	40	58	75

Temperatures in centigrade of the reacting absorbents in the "to and fro" canister at the front (F), middle (M), and distal (E) thirds of the canister under identical conditions. The thermometer was placed with its tip half way between the center and side of the canister at the front (F) third, middle (M), and end (E) third of the canister.

third of the canister with its tip 4 cm. below the canister edge, the temperature rose to 65 C. within the first hour. In the middle, with the thermometer in the same position, it was 60 C., and in the distal third it was 47 C. As the charge became progressively exhausted, the middle temperature rose and the front fell, and finally that of the distal third rose and the front and middle fell. The graphs are similar to those obtained with soda lime under the same conditions.

Canisters 8×13 cm. charged with this barium lime mixture have an air space averaging 400 cc. The inter- and intra-granular air space has been shown to be of importance since most efficient absorption is obtained when the tidal volume of the patient is accommodated as nearly as possible by this air space in the canister (2). The space allowed by the barium lime pellets compares favorably with that of standard soda lime. The number of particles per cubic centimeter of space occupied by the absorbent is less than that of soda lime, averaging 18-20 compared with 26-32 for soda lime. This is probably due to the uniformity of size of the pellet. The surface of the absorbent exposed to atmospheres to be freed of carbon dioxide is the most important single factor which influences efficiency. The increased surface area in this form is an advantage.

The absorbent material contributes to the resistance to respiration found in rebreathing units. The greater the surface, the greater the friction produced, and, therefore, the more resistance encountered. In a canister 8×13 cm., charged first with 4×8 mesh soda lime and then with barium lime pellets, a tidal volume of 500 cc. and a respiratory rate of 20 per minute, in a "to and fro" manner were used. A water manometer connected to the mask indicated the resistance developed by both, as measured by the negative pressure on inspiration. The difference between that caused by soda lime and that by barium lime was of no practical significance. With the former it was 2.5 mm.; with the latter, 2.4 mm. of water.

The dust factor, which is a highly objectionable feature of soda lime particularly in the "to and fro" system, was also studied. There was no tendency to fragmentation of the pellets during or after use, either clinically or experimentally. In clinical trials using the manually held canisters, there was no fragmentation of the pellets. The freshly prepared pellets are frequently coated with a very thin layer of chalky dust which is easily blown off in "to and fro" units. After such a blowing and collecting of the dust, none was found in the mask. Once this dust is removed, none forms during use.

Extensive clinical experience with the barium lime absorbent has confirmed many of the points suggested by the laboratory experiments. It is unfortunate that laboratory experiments on this project cannot be directly and unreservedly applied to clinical anesthesia. Numerous factors, such as the patient's reaction to preoperative sedation, the basal metabolic rate, together with length of the operation, and stimulation by the surgeon, will affect the respiratory exchange and the output of carbon dioxide. Such conditions vary not only from patient to patient but from time to time in the same individual. They usually cannot be standardized. No precise correlation, therefore, can be drawn between the laboratory experiments on carbon dioxide absorption and their practical application in the anesthetized human being.

In the clinical use of the barium lime absorbent, however, an attempt was made to eliminate as many of these variables as possible. All patients were adults, and none was believed to have any gross pathological changes in the respiratory system. Premedication was given according to the technic of Waters (3) and consisted of appropriate quantities of morphine sulphate and scopolamine hydrobromide in a ratio of 25:1 one to one and a half hours prior to beginning anesthesia. The operative procedures were those ordinarily encountered in a general hospital, except that no cases of thoracic surgery were included in this series. All anesthesia was administered with the closed carbon dioxide absorption technic of Waters. Throughout the study, nitrous oxide and oxygen were used for induction, and ethyl ether for maintenance. The canisters containing the barium lime mixtures were of the "to and fro" cylindrical type, 8 × 13 cm. in size. Patients were induced in the usual manner without the absorbing unit in place. Once a sufficient depth of anesthesia was obtained, and hyperpnea was no longer deemed necessary, the canister was placed in the system without loss of the contents of the breathing bag.

The longest continuous use in any one single instance was one hundred eleven minutes. Analyses* for carbon dioxide were made at approximately ten-minute intervals on samples removed from the breathing bag during this interval. Concentrations were found never to rise above 0.1 per cent. Such excellent absorption of carbon dioxide for a prolonged period of time is to be anticipated from the nature of the constituents of the barium lime mixture. No rest period was found necessary to reestablish the efficiency of the compound.

In order to determine the absorptive powers of the barium lime mixture throughout the life of a single charge, analyses for carbon dioxide in the breathing bag were undertaken throughout a number of successive clinical anesthetics. These anesthetics were separated from one another by periods of time varying from a few moments to several hours. The results are shown in table 3.

Repeated analyses under as nearly identical conditions as possible indicate the above figures to be typical of the prolonged efficiency of this compound.

It is to be noted that the absorptive efficiency of the barium lime mixture remains high until the charge nears complete exhaustion. The compound then quickly becomes inefficient, and carbon dioxide accumulates rapidly. Analyses performed on the last case of the above series (J. Y.) are shown in figure 1.

The first manifestation of carbon dioxide excess was hyperpnea. Then followed an increase in blood pressure and finally a tachycardia. The increased pulse rate was not constantly present. It seemed to

* These analyses were carried out on a single modified Hemple type absorption pipette, connected to a modified 100 cc. burette calibrated to 30 cc. in 0.1 cc. divisions. This apparatus allows for rapid (15 sec.) analyses. Error is ± 0.1 per cent.

TABLE 3
 BARIUM LIME ABSORBENT

% carbon dioxide in breathing bag at approximately ten-minute intervals to exhaustion of barium lime mixture. Total time in use—10 hours, 45 minutes.

Case	Canister in Use		Per Cent CO ₂ in Breathing Bag													
	In Each Case Minutes	Total Time Used Minutes	Time in Minutes after Canister Placed in System													
			10	20	30	40	50	60	70	80	90	100	110			
M.D.	40	40	0.0	0.0	0.0	0.0										
R.R.	15	55	0.0													
B.M.	15	70	0.0													
B.M.	35	105	0.0	0.0	0.0											
R.S.	111	216	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.1	
A.S.	84	300	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.1	0.1				
E.B.	55	355	0.1	0.1	0.1	0.1	0.1									
E.H.	30	385	0.2	0.1	0.2	0.3	0.3									
J.L.	15	400	0.5													
H.P.	45	445	0.5	1.0	0.8	0.4										
R.P.	45	490	0.8	0.8	0.7	1.0										
W.H.	60	550	1.0	0.8	0.9	0.9	1.4	1.3								
J.Y.	95	645	1.3	1.7	1.7	2.0	2.1	3.4	4.3	7.0	10.0					

occur only after the patient had been exposed to hypercapnea for some time.

At no time was dust observed in any appreciable quantity on the anesthesia apparatus. It was noted that when barium lime was used no dust was observed about the lips and cheeks of the patient when the anesthesia had been concluded. In this series of cases no laryngospasm due to inhaled dust particles was observed.

Repeated recordings of the temperature in the canister were found to parallel closely those demonstrated in the laboratory. The 8 × 13 canister with three thermometers measuring temperatures in three sites in the center of the canister was used. The results are shown in figure 2.

For comparison, a canister filled with 4 × 8 mesh soda lime was run under similar conditions. The temperatures are recorded in figure 3.

A survey of these figures indicates that while the temperatures of the two absorbing agents do not vary radically, those of the soda lime mixture are higher than those of the barium lime. The site of maximum absorption changes from that portion of the canister nearest the face piece to that nearest the breathing bag as the mixture becomes exhausted. The cooling of the temperature in all parts of the canister indicates lessened absorption. This coincides with the clinical findings of carbon dioxide increase, i.e., progressively increasing hyperpnea, blood pressure, and pulse rate.

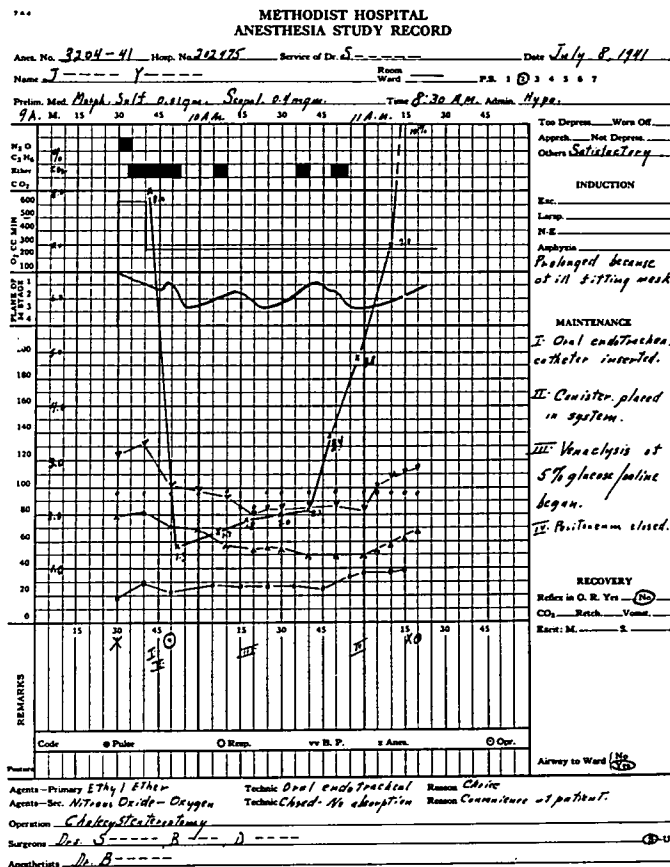


FIG. 1. Anesthesia study record showing effects of carbon dioxide accumulation. Carbon dioxide in breathing bag recorded in per cent.

SUMMARY

The chemistry of carbon dioxide in rebreathing appliances used for anesthesia has been reviewed. An experimental study in the laboratory on the efficiency of barium and calcium hydroxide mixtures has

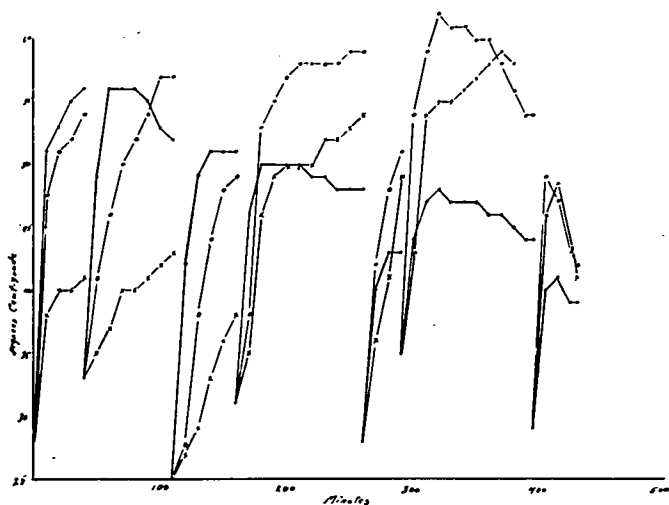


FIG. 2. Temperature recordings of three thermometers with barium lime mixture as absorbent. Legend—thermometer nearest mask, . — . — ., in center of canister, o — — — o, nearest breathing bag, x — — — x.

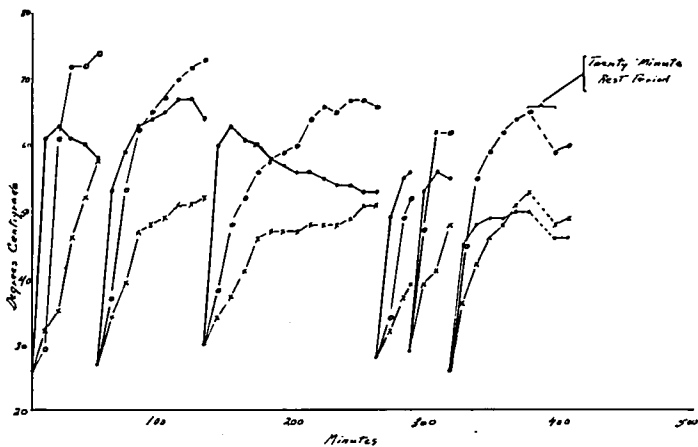


FIG. 3. Recordings of temperature in three portions of canister filled with soda lime. Legend as in figure 2.

been presented and data obtained compared with that of soda lime under similar conditions.

Barium lime mixture, prepared in the form of pellets, has a greater degree of hardness and is comparatively free from dust. It absorbs carbon dioxide effectively and compares favorably in this respect with soda lime. The temperatures resulting from the reaction show no significant deviation from that seen with soda lime. Resistance due to the absorbent varies little from that obtained with soda lime. In clinical trials the signs of carbon dioxide excess were no more apparent than with soda lime. The pellets are non-hygroscopic, do not disintegrate under varying conditions of clinical and experimental use. They withstand the mechanical abuse of the manually-held canisters better than soda lime. The periods of exhaustion followed by regeneration of activity after rest, as noted with soda lime, are not apparent with this mixture. The required bulk for efficient absorption is the same for both absorbents. The barium lime mixture is worthy of further clinical trial and experimentation.

REFERENCES

1. Adriani, J., and Rovenstine, E. A.: Experimental Studies on Carbon Dioxide Absorbers for Anesthesia, *Anesthesiology* 2: 1-19 (Jan.) 1941.
2. Adriani, J., and Byrd, M. L.: A Study of Carbon Dioxide Absorption Appliances for Anesthesia, *Anesthesiology* 2: 450-455 (July) 1941.
3. Waters, R. M.: A Study of Morphine, Scopolamine, and Atropine and Their Relation to Preoperative Medication and Pain Relief, *Texas State J. Med.* 34: 304, 1938.

COMING EXAMINATIONS

The Part II (Oral) Examinations for certification by the American Board of Anesthesiology, Inc., will be held at the Ritz-Carlton Hotel, Atlantic City, New Jersey, June 6 and 7, 1942. Applications should be filed at the headquarters' office by March 7, 1942. If the Part I (Written) Examinations has been passed successfully, or if an application is on file at headquarters, it will not be necessary to make separate application for the oral examinations. Sec., Paul M. Wood, M.D., 745 Fifth Avenue, New York City.

OFFICERS ELECTED

At the conclusion of the meeting of the Section on Anesthesia of the Southern Medical Association, held on November 12, 1941 in St. Louis, Missouri, the following officers were elected for the ensuing year:

President: Russell F. Bonham, M.D., Houston, Tex.

Vice-President: Merrill C. Beck, M.D., New Orleans, La.

Secretary-Treasurer: John Adriani, M.D., New Orleans, La.