A CLINICAL STUDY OF CARBON DIOXIDE ABSORPTION DURING ANESTHESIA

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Since 1923 when Waters first applied the carbon dioxide absorption principle of rebreathing to inhalation anesthesia, various absorbent materials have been produced in an effort to gain maximum efficiency of carbon dioxide absorption from anesthetic atmospheres. Soda lime (sodium and calcium hydroxide) and baralyme (barium and calcium hydroxide) are the chemical absorbents which have gained wide acceptance during the last few years. Soda lime has been used for almost twenty years. During this time many changes have been made in an attempt to prevent excessive heating and to minimize crumbling and the formation of dust (2). The percentage of sodium hydroxide in soda lime has been reduced to approximately 5 per cent. The remainder of the material is made up of calcium hydroxide with moisture content which varies in different products from 1½ to 18 per cent. There has been a great deal of discrepancy in opinion as to the efficiency of the various soda limes as related to their moisture content. Soda lime, procured on the open market, may vary as previously stated.

In 1941, Adriani and Ravenstine (1) reported that the analysis of absorption shows practically no difference between the efficiency or utility of wet and dry soda lime. They also stated that when soda lime becomes exhausted from use, reactivation takes place if the absorbent is allowed a period of rest. In 1942 Adriani and Batten (2) confirmed previous observations on the peak efficiency of soda lime with reactivation after a period of rest and reported that a peak of efficiency did not occur when baralyme was used as the absorbent material. They found that baralyme absorbed carbon dioxide efficiently to the exhaustion point. Periods of rest did not reactivated the substance. They found that baralyme compares favorably with soda lime in absorption efficiency. In 1943 Conroy and Seevers (3) observed that an increase in carbon dioxide output shortened the effective life of the absorbent in direct proportion to such increase. Adriani’s previous results were confirmed by means of a mechanical lung which was devised for testing anesthetic appliance.

In 1941 Kilborn (4) made the first preliminary report on the efficiency of baralyme as a carbon dioxide absorbent. He used a low moisture type of granular soda lime as a control. In this report he mentioned the peaking effect and partial reactivation of soda lime after a
period of rest. He found that baralyme, on the average, showed a run of two to four hours longer per canister and produced no peaking effect. Batten, in 1943 (5), reported that the efficiency of carbon dioxide absorption, using baralyme, remains constant throughout the life of the charge. No rest period is needed for reactivation and exhaustion, when it occurs, is rapid and irreversible. In 1943, Waters (6) reported that under operating conditions no chemical tests for soda lime can safely replace the meticulous and discriminating observation of the patient by the anesthetist.

The majority of previous reports on the efficiency of carbon dioxide absorption have been based on the results of laboratory investigation. Mechanical lungs have been devised for the purpose of simulating, as closely as possible, the tidal volume, rate of respiration, rate of respiratory excursion and carbon dioxide output in the average patient.

The report of this investigation is the result of studies which were made in the operating room under normal operating conditions. The circle type of gas machine was used throughout this clinical investigation, pressure readings were taken in the system at all times and at no time did the resistance to respiration exceed 1 cm. of water either on expiration or inspiration except in cases of open thoracotomy when positive pressure anesthesia was being administered intentionally.

In gas anesthesia using closed rebreathing systems, gas analysis for carbon dioxide may be made using standard methods of gas analysis, if ether is not used for anesthesia. When ether is used other methods must be devised to eliminate its influence on the accuracy of analysis. As ether was employed for anesthesia during these investigations, a method of analysis for carbon dioxide was developed. The method is based on the reaction of carbon dioxide with barium hydroxide solution and titration of the unreacted barium hydroxide with hydrochloric acid.

A measured gas sample was taken and passed through a known volume of standard barium hydroxide solution. The carbon dioxide reacted with the barium hydroxide solution and the remaining unreacted barium hydroxide was titrated with a standard hydrochloric acid solution of the same normality to the phenolphthalein end point. The number of cubic centimeters of hydrochloric acid used subtracted from the total number of cubic centimeters of barium hydroxide gave the number of cubic centimeters remaining which was read directly as percentage of carbon dioxide. For example a total volume of 25 cc. of barium hydroxide minus a volume of 24 cc. of hydrochloric acid equals 1 cc. of barium hydroxide used by carbon dioxide and equals 1 per cent carbon dioxide.

Measured gas sample = 100 cc.
Measured volume of Ba(OH)$_2$ = 25 cc.
Normality of Ba(OH)$_2$ = 0.0815N
Normality of HCl = 0.0815N
1 cc. of Ba(OH)$_2$ of 0.0815N = 1% CO$_2$ at 25 C. and 29.9'' Hg
The apparatus consisted of a Fisher technical gas analysis buret mounted on a frame support and connected to an absorption chamber. The absorption chamber was devised from a Friedrich’s condenser as it gave a maximum absorption for a minimum of solution.

Two Schellbach automatic burets of 25 cc. capacity were attached to the same stand. One buret was connected to a 2 liter bottle of the standard barium hydroxide solution and was used for measuring out 25 cc. portions of barium hydroxide. The other buret was connected to a 2 liter bottle of the standard hydrochloric acid solution and was used for titration of the Ba(OH)$_2$ solution.

Two Heidbrink gas machines were used interchangeably throughout the tests. The double charge type of canister was used. Each chamber of the canister was of 750 cc. volume capacity and the weights of samples of absorbents used averaged 1 1/2 pounds charge per chamber.

"T" connections were inserted at the inspiratory and expiratory sides of the gas machine so that analysis of the carbon dioxide output of the patient and the carbon dioxide intake could be measured at all times. Hose connections were made from the machine to the gas analyzer. A sample of 100 cc. of gas was first withdrawn and discarded to free tube connections of dead space. A second 100 cc. of gas was withdrawn and this was the sample used for analysis.

A Connell spirometer bag was attached to the outlet of the absorption canister. Temperature measurements of the gases in the bag were made using a thermometer inserted in a "Y" connection between the spirometer bag and the absorption canister. Measurements of tidal volume and temperature of the gases in the bag were made at intervals throughout the tests.

Lapse of time between cases was minimized as much as possible to get a continuity of run for the absorbents tested. This was done to determine whether and to what extent "peaking" (apparent exhaustion of absorbent short of its true total carbon dioxide combining capacity) occurred in the various absorbents tested. By using two Heidbrink machines it was possible to change all instruments of measurement from one machine to the other in use with very little lapse of time between cases.

It was of utmost importance to obtain as completely and accurately as possible the data collected while running these tests so that each curve plotted for the various absorbents tested would be comparative one with the other. To make these curves comparative, and for calculations of the absorbent life, the essential measurements made were time, percentage of carbon dioxide inspired, percentage of carbon dioxide expired, respirations per minute, barometric pressure, and temperature of the gases in the rebreathing bag. Measurements of pulse and blood pressure were taken also to correlate them with carbon dioxide build up, when the absorbent became inefficient. Other measurements of
metabolic oxygen and room temperature were also made to determine whether they influenced the tests.

Measurements of time, respirations per minute, barometric pressure, and temperature of the gases in the rebreathing bag were taken at the same intervals as the analysis of percentage of carbon dioxide inspired and percentage expired. These intervals of time at which tests were taken were at no set limits. Instead, they were made whenever it was possible to eliminate the influence of dilutions by additions of gases as well as the influence caused by aspirating the patients.

The volume of a gas varied with temperature and barometric pressure. Since the volume of the gas measured is dependent upon these factors, corrections to the same conditions are necessary to make the tests comparative. The value of 60 F. and 30 inches of mercury was selected for the standard value of comparison since it is very widely used as such in gas volume measurements. The factor used in the tests is the result of the correction of the average temperature in the rebreathing bag and the barometric pressure to 60 F. and 30 inches of mercury.

The gas volume measured contained moisture from two sources: from the patient's breath and that formed as one of the end products of the reaction of the absorbent. The humidity of the gas volume from this moisture was found to be 100 per cent at all times. Humidity of 100 per cent at a specific temperature is also known as a saturated gas volume. Since the water vapor was a part of the gas volume measured, it was reported present in all the gas volume measurements made. All test specifications stated, therefore, that the gas volume measurements were corrected to 60 F. and 30 inches of mercury saturated gas volume.

From the data collected, curves were plotted for the various absorbents tested. The percentages of carbon dioxide were plotted as ordinates and time in minutes as abscissas. Values of expiratory carbon dioxide as well as inspiratory carbon dioxide were plotted on each graph to show the comparison of one with the other as the absorbent became less efficient in its absorption of carbon dioxide. Since there is no set value of carbon dioxide leakage which is considered harmful to a patient during anesthesia, a value of 0.6 per cent of carbon dioxide was used as the leakage point and end of efficient life of the absorbent in all curves.

The lapse of time between cases was indicated by a vertical dotted line and the amount of time of the lapse was shown. The amount of time to the end of each case and the total to 0.6 per cent carbon dioxide were also indicated. In some instances one case was of sufficient duration to last to the end of the absorbent life.

The curve showing the time of life of an absorbent in itself is no true indication of this value, when time is considered alone. Average rate of flow of the gas, average percentage of carbon dioxide output, and total volume of carbon dioxide to the end of the efficient life of the
absorbent should be considered for complete evaluation. The following
descriptive calculations illustrate how the data collected were used to
obtain the desired values.

Correction factor for converting gas volume to 60 F. and 30 inches
of mercury saturated gas volume.

Original Conditions

\[ P = \text{Barometric pressure observed} \]
\[ T = \text{Absolute temperature plus the average temperature of gas in the bag} \]

Final Conditions

\[ P_1 = \text{Barometric pressure to which corrected} \quad 30 \text{ inches of mercury} \]
\[ T_1 = \text{Absolute temperature plus the temperature to which corrected} \quad 460 + 60 \text{ F.} \]
\[ F = \text{Factor resulting from the calculations of these values} \]

\[ F = \frac{P}{T} \cdot \frac{T_1}{P_1}. \]

The gas volume was reported as saturated and therefore no calculation
was necessary to account for the influence of the water vapor on the gas
volume.

Conversion of average tidal volume and respirations per minute to
cubic centimeters per minute of carbon dioxide and oxygen \footnote{Since the anesthetic gases present in
the rebreathing bag, as far as gas volume measurements are concerned, were there only as diluents of carbon
dioxide concentrations, the gas volume measurements in the tests were considered as being mixtures of carbon
dioxide and oxygen.} at 60 F. and 30 inches of mercury.

Average tidal volume \times \text{average respirations per minute} \times \text{Factor} 
\quad \text{cc. per minute of carbon dioxide + oxygen}.

Conversion of volume per minute of carbon dioxide and oxygen to
volume per minute of carbon dioxide.

Average percentage of carbon dioxide expired \times \text{cc. per minute of carbon
dioxide + oxygen} = \text{cc. per minute of carbon dioxide}.

Conversion of cc. per minute of carbon dioxide + oxygen; also carbon
dioxide to over-all total \footnote{In curves in which more than one case was required to reach 0.6 per cent
carbon dioxide leakage, the total volumes of carbon dioxide for the individual cases were added to give the
over-all total cubic centimeters of carbon dioxide to 0.6 per cent carbon dioxide leakage. In
cases in which one case was sufficient to reach 0.6 per cent carbon dioxide leakage, the total
volume of carbon dioxide for that case to 0.6 per cent carbon dioxide leakage was used for the
over-all total.} cc. to 0.6 per cent carbon dioxide leakage.

Total time \times \text{cc. per minute carbon dioxide + oxygen} = \text{total volume of carbon dioxide + oxygen}.

Total time \times \text{cc. per minute carbon dioxide} = \text{total volume of carbon dioxide}. 
From the over-all total cc. of carbon dioxide = oxygen also cc. of carbon dioxide to 0.6 per cent carbon dioxide leakage the over-all average rates of cc. per minute carbon dioxide + oxygen and cc. per minute carbon dioxide were determined by dividing them by the total time to 0.6 per cent carbon dioxide leakage.

The over-all average cc. per minute of carbon dioxide divided by the cc. per minute of carbon dioxide + oxygen gave the over-all average percentage of carbon dioxide output.

Over-all average percentage of carbon dioxide output and the time to 0.6 per cent of carbon dioxide were found to vary to such an extent from curve to curve that they were not used for comparative purposes. The value found to be most accurate in comparison of one curve with the other was the over-all total volume of carbon dioxide to 0.6 per cent carbon dioxide and this was the value used in the comparisons made.

From the curves plotted, the following facts were learned:

1. The "low moisture" soda lime of 1.5 per cent moisture content, as seen in curves "A" and "B" (plates 1 and 2), was found to be an inefficient absorber of carbon dioxide. It picked up carbon dioxide efficiently for only a short period of time. After a rest period, renewed activity then occurred for another short period of time and is believed to be the result of absorbed and re-distributed moisture rather than of an exchange between Na₂CO₃ and Ca(OH)₂. This soda lime is also believed to be of the commonly called "peaking type."

\[ \text{Expired CO}_2 \]
\[ \text{Inspired CO}_2 \]

\text{PLATE 1}

\text{Curve A. This curve illustrates the type of life to be expected of a low moisture soda lime. Low moisture soda lime is an inefficient carbon dioxide absorber. This sample gave 67 minutes of use to .6 per cent carbon dioxide leakage picking up 18,600 cc. carbon dioxide in that time for its primary absorption period. After a lapse of 8 days, 2 hours, 48 minutes, sealed in an air-tight container, it was again used. It then gave 33 minutes of use to .5 per cent carbon dioxide spillage picking up 7,100 cc. carbon dioxide in that time.}
2. The "low moisture" soda lime of 1.5 per cent moisture content, as shown in curve "H" (plate 3), illustrates that if an operation is of sufficiently short duration the "penking effect" will not be visible, as the use of the absorbent was halted before the carbon dioxide in the system had the opportunity to build up in concen-

PLATE 2

Curve B. This curve illustrates the type of life to be expected of a low moisture soda lime. Low moisture soda lime is an inefficient carbon dioxide absorber. This sample gave 58 minutes of use to .6 per cent carbon dioxide spillage picking up 24,000 cc. carbon dioxide in that time for its primary absorption period. After a lapse of 7 days, 4 hours, 4 minutes, sealed in an air tight container, it was again used. It then gave 84 minutes of use to .6 per cent carbon dioxide spillage picking up 30,000 cc. carbon dioxide in that time. The renewed activity after the rest period is believed to be the result of absorbed and redistributed moisture (all gas volume measurements corrected to 60 F. and 30 inches mercury saturated gas).

PLATE 3

Curve H. The data in this curve lack measurements of tidal volume, respirations, barometric pressure and gas temperatures. It is therefore incomplete and cannot be used for comparison with these curves containing complete data. However, it can be used to illustrate the absorption of moisture on low moisture soda lime from the ambient during the first case, the redistribution of that moisture during a 3 hour 16 minute rest period and followed by a subsequent absorption period. (Note high concentration carbon dioxide built up in the system during the early phase of induction while the soda lime canister was not in use.)
tration. After a rest period, renewed activity in this type of soda lime occurred for another period of time and is believed to be the result of absorbed and redistributed moisture. As the data collected in this curve were incomplete, the curve could not be used for comparison with those curves containing complete data.

3. The “high moisture” soda lime of 15 per cent moisture content, as shown in curve “1” (plate 4), was found to absorb carbon dioxide efficiently to the exhaustion point. Following rest periods produced no reactivation for further efficient absorption of carbon dioxide. This also illustrates that the “high moisture” soda lime used shows no commonly called “peaking effect” throughout its active life. Apparently, the 15 per cent moisture present in the sample was the cause of continued activity to the exhaustion point, rather than an exchange between Na₂CO₃ and Ca(OH)₂. As the data collected in this curve were incomplete, the curve could not be used for accurate comparison with those containing complete data.

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**PLATE 4**

**CURVE I.** The data in this curve lack measurements of tidal volume, respirations, barometric pressure and gas temperatures. It is therefore incomplete and cannot be used for comparison with the curves containing complete data. However, the curve illustrates the effect of the type of case on the life of the absorbent. Lobectomies and decortications influence the accuracy of the data because of leakage and dilutions throughout the operations. It also shows that effective life of the absorbent is present to the exhaustion point. A rest period produces no reactivation for further efficient absorption of carbon dioxide.
CURVE C. This curve is the result of data collected on decortications. The influence of these gases on the curve is negligible and the curve can be used for comparison with those containing accurate comparable data. The influence of decortications and lobectomies is, in general, a diluting effect on the gases in the system. If diluting had occurred this curve would result in an apparent longer time before .6 per cent carbon dioxide spillage was detected. Therefore, dilution is not an influence on the results shown here. The curve indicates that 241 minutes of use was obtained to .6 per cent carbon dioxide spillage with 87,920 cc. of carbon dioxide being picked up by the soda lime. This can be considered to represent 241 minutes of use by a patient with a tidal volume of 400 cc., 27.7 respirations per minute with an expiration of 3.16 per cent carbon dioxide. (Note elevation of expired carbon dioxide paralleling the carbon dioxide built up in the anesthesia apparatus.)

CURVE D. This curve indicates that 344 minutes (5 hours, 44 minutes) of use was obtained to .6 per cent carbon dioxide spillage with 87,980 cc. of carbon dioxide being picked up by the soda lime. This can be considered to represent 344 minutes of use by a patient with a tidal volume of 400 cc., 26.3 respirations per minute with an expiration of 2.7 per cent carbon dioxide (all gas volumes are corrected to 60 F. and 30 inches mercury saturated gas). (Note there is no increase in blood pressure or pulse rate at the time inspiratory carbon dioxide reached 1.4 per cent during the second hour of anesthesia.)
4. Curves “C” and “D” (plates 5 and 6), contain data which are complete and were used for comparison with others containing complete data. The “high moisture” soda lime of 15 per cent moisture was the same as was used in curve “I” (plate 4). Therefore, the same facts stated for curve “I” hold true for curves “C” and “D” (plates 5 and 6). By comparing the overall total volume of carbon dioxide to 0.6 per cent carbon dioxide leakage with curve “E” (plates 7, 8 and 9), curve “F” (plates 10, 11, 12 and 13), and “P” (plate 14), it can be seen that this sample of soda lime was nearly as good as baralyme during its efficient life period.

![Graph](image)

**PLATE 7**

**Curve E.** This curve indicates that 298 minutes (4 hours, 38 minutes) of use was obtained to .6 per cent carbon dioxide spillage with 101,170 cc. of carbon dioxide being picked up by the baralyme. This can be considered to represent 298 minutes of use by a patient with a tidal volume of 400 cc., 28.4 respirations per minute with an expiration of 2.9 per cent carbon dioxide.

5. The baralyme sample in curve “N” (plate 15), although an experimental formula, illustrates the characteristic of all baralyme; that is, the absorbent life is efficient in carbon dioxide absorption to the exhaustion point. Following rest periods produce no reactivation for further efficient absorption of carbon dioxide. This also illustrates that there is no “peaking” baralyme. As the baralyme sample in this curve was experimental the results could not be used for comparison with standard samples used.

6. The baralyme used in curves “E” (plate 7), “F” (plate 10), and “P” (plate 15) was a standard product and the data being complete and accurate made the curves available for comparison with soda lime curves “A” (plate 1), “B” (plate 2), “C” (plate 5), and “D” (plate 6). As can be seen, curves “E” (plate 7), “F” (plate 10), and “P” (plate 15) illustrate that all baralyme
PLATE 8. Clinical course of the 3 patients whose carbon dioxide intake and output were plotted in Plate 7. Note that there was no change in pulse, respiration or blood pressure of the patients during the fifth hour of anesthesia although the inspired carbon dioxide had reached 1 per cent and was maintained at that level for approximately 35 minutes.
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absorbs carbon dioxide efficiently to the exhaustion point, and comparing these curves with "A" (plate 1), "B" (plate 2), "C" (plate 5), and "D" (plate 6), it can be seen that baralyme is more efficient than "high moisture" and "low moisture" soda lime.

**PLATE 10**

**Curve F.** This curve indicates 284 minutes (4 hours, 44 minutes) of use was obtained to .6 per cent carbon dioxide with 98,900 cc. of carbon dioxide being picked up by the baralyme. This can be considered to represent 284 minutes of use by a patient with a tidal volume of 400 cc., 26.1 respirations per minute with an average expiration of 3.33 per cent carbon dioxide. (All gas volume measurements are correct to 60 F. and 30 inches mercury saturated gas.)

It becomes apparent, therefore, from the preceding facts, that moisture promotes the efficient absorption of carbon dioxide.

It is believed that when sufficient moisture is present it permeates the absorbent particles fairly completely. The moisture then dissolves the carbon dioxide gas and some carbonic acid is formed, $\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3$. The carbonic acid in turn reacts rapidly with the bases present, producing the carbonate and additional moisture to dissolve more carbon dioxide and form more carbonic acid and so on until the reaction become inefficient because of the approaching completion of reaction.

Dry carbon dioxide and dry absorbents will not react. Absorbents with a sufficiently low moisture content react poorly. It is thus evident why "low moisture" soda lime of 1.5 per cent moisture content absorbs carbon dioxide inefficiently.

In a "low moisture" absorbent it is believed that the reaction is inefficient because the moisture is not present in a sufficient quantity to form sufficient carbonic acid for rapid and continuous reaction with the absorbent. The reaction proceeds efficiently until the heat of reaction causes this small amount of moisture to be driven away from the particles, making them so dry that carbonic acid cannot form. Further reaction then proceeds very incompletely. However, moisture is still present in the canister.
PLATE 11. Even clinical course to be expected during the efficient carbon dioxide absorption.
PLATE 12. Graphic outline of blood pressure, pulse and respiration. In the second case shown in curve D note that there is no increase in blood pressure or pulse rate at the time the inspired carbon dioxide reached 1.4 per cent during the second hour of anesthesia.
During a rest period the canister with its contents cools to room temperature. The moisture is condensed and redistributed on the particles of the absorbent. Then sufficient moisture is present in the partially exhausted soda lime to form carbonic acid with the exhaled carbon dioxide and an additional absorbing period can be expected. Three hours was found to be a sufficient time for this condensation and redistribution.

Heretofore it has been stated that all soda lime “peaked” and that regeneration occurred because of an interchange of the sodium carbonate and calcium hydroxide during the rest period (1). This interchange during the rest period then resulted in renewed activity. As it has been found clinically that a sample of “high moisture” soda lime, 15 per cent moisture content, did not show any “peaking” effect and that a sample of “low moisture” soda lime of 1.5 per cent moisture content did show a “peaking” effect, it becomes evident that it is the amount of moisture present in the soda lime that controls its activity rather than the exchange between sodium carbonate and calcium hydroxide.

The minimum amount of moisture present in soda lime still to give efficient absorption was not determined in the work done. From the experiments carried out, it is evident that 1.5 per cent moisture content is not sufficient moisture for an efficient reaction, and 15 per cent moisture content is sufficient to give an efficient reaction.

Curve “Y” (plate 16) illustrates that exposing a drum of “high moisture” soda lime to the atmosphere results in its becoming a “low moisture” soda lime. The moisture present in soda lime is there as physical moisture; physical moisture, of course, meaning it is not present in chemical combination with the hydroxides.

Physical moisture is volatile; that is, it can easily be evaporated from a substance. This is the reason why “high moisture” soda lime loses its moisture on exposure to the atmosphere.

In a previous paragraph it was stated that there is no “peaking” baralyme. An ordinary batch sample of baralyme was exposed to the atmosphere in the same manner as “high moisture” soda lime and the results plotted in curve “Y” (plate 16). It can be seen that there is very little variation in the moisture content of the baralyme and at times an increase in moisture takes place. For all practical purposes, there is no loss in moisture content in baralyme upon exposure to the atmosphere under normal conditions of temperature and humidity.

Baralyme is composed of 20 per cent barium hydroxide combined with 80 per cent calcium hydroxide in a homogenously mixed pellet. The barium hydroxide has eight waters of crystallization combined as part of its chemical composition (Ba(OH)\(_2\).8\H_2O). A compound with waters of crystallization is known as a hydrate.

Waters of crystallization being chemically combined water, which are also known as definite percentages of water, remain unchanged.
PLATE 13 (Continued). This anesthesia record corresponds to the third case shown in curve P. Note that there is no clinical evidence of carbon dioxide build up as shown in pulse and blood pressure curves, although 2 per cent carbon dioxide is being inspired by the patient during the second hour of anesthesia.
during moderate changes in the moisture content of the atmosphere. Even should these moderate changes in the atmosphere become extreme, the moisture lost by the hydrate is slight. Also, when normal atmospheric conditions return, that small amount of lost moisture will be picked up to give the hydrate its normal chemically combined moisture again. Variations in the moisture content of the atmosphere explain why there are slight variations in the moisture content of the hydrate.

Although these slight losses of moisture do occur in the hydrate, they do not affect the efficiency of the absorption of the absorbent. As moisture is given off by the patient and is one of the reaction products of the absorbent, any of these moisture losses of the hydrate is regained while the absorbent is in use. Because of stability of moisture content, baralyme will absorb carbon dioxide efficiently at all times. Hence there can be no “peaking” baralyme.

**Curve P.** This curve indicates that 195 minutes of absorption time was obtained to .6 per cent carbon dioxide spillage. This represents 195 minutes of use by a patient during lobectomy whose average tidal volume was 400 cc., average respirations 44 per minute with an average carbon dioxide output of 3.2 per cent. A total of 101,800 cc. of carbon dioxide was absorbed during the 195 minute interval of time.

**Curve N.** This curve illustrates that effective life of the absorbent is present to the exhaustion point. A rest period produces no reactivation for further efficient carbon dioxide absorption.
Further facts learned from the curves plotted are enumerated below.

1. Curves "C" (plate 5) and "D" (plate 6) for high moisture soda lime and "F" (plate 10) and "P" (plate 14) illustrate that the total time of efficient absorption of the absorbents is not a set value and therefore time is not a true value clinically for evaluating the life of the absorbent. This is evident if the curves are closely examined. As can be seen, flow rate and percentage of carbon dioxide are the important values. If either one of these two values of flow rate or percentage of carbon dioxide expired is altered so as to become a variable, then time becomes a variable and is not usable as a value for comparing different curves.

2. Tidal volumes, respirations and carbon dioxide expired vary from patient to patient in the data on the curves plotted.

3. Under certain conditions of anesthesia the carbon dioxide expired by the anesthetized patient approaches that of a conscious person. This is particularly true when light premedication is used, light anesthesia is maintained, or when ether is used for anesthesia. Ether increases the respiratory rate. Some other anesthetics depress it.

4. In most curves it can be seen that as exhaustion of the absorbent is reached, the expiratory carbon dioxide of the patient increased as the inspiratory carbon dioxide increased.
5. Percentages as high as 2 per cent carbon dioxide are often impossible to detect by clinical observations of the patient's tidal volume, respiratory rate, pulse and blood pressure changes. Influences of ether, light anesthesia, and pain stimulus detract from the ability to judge carbon dioxide build-up by simple observation when the absorbent is becoming inefficient. The only satisfactory method of determining these percentages is by analysis. If blood carbon dioxide analysis could be taken when these small percentages of carbon dioxide are present in the inspiratory gas, perhaps the amount of physiologic effect of these small percentages on the patient could be learned.

6. Cooling of the canister, or a cool canister, is a very poor indication for determining the end of the absorbent life. A cooling canister may be the result of the absorbent being cut out of the system. It may result because the reaction of the absorbent has not proceeded far enough to heat the canister, it may reflect the reaction resulting from a very low carbon dioxide expiration, or it may be because the absorbent no longer has any absorptive ability. A hot canister may indicate the extremely efficient absorption of carbon dioxide, it may represent a very high carbon dioxide expiratory rate, or it may be that the absorbent is exhausted but the heat of the canister has not yet dissipated. From these numerous possibilities it is evident how difficult it would be to determine the end of the absorbent life by these signs.

Laboratory tests have shown that "low moisture" soda lime "peaks." "High moisture" soda lime does not "peak" and gives an absorbent life approaching that of baralyme. Baralyme never "peaks" and has an absorbent life somewhat longer than "high moisture" soda lime. "High moisture" soda lime may become "low moisture" soda lime. Moisture is the essential factor to give an efficiently active absorbent.

These phenomena were verified by the clinical work performed during this investigation.

It is necessary to observe the same fundamental factors when attempting to correlate the laboratory results with clinical findings. These factors are flow rate, gas temperature, humidity of the gas at the same temperature found clinically, barometric pressure, and the percentage of carbon dioxide of the gas mixture. Flow rate, humidity, and percentage of carbon dioxide are maintained at a constant level. As in clinical procedures, barometric pressure and gas temperature are corrected to 60 F. and 30 inches of mercury.

In clinical investigations the patient comes first and the experiment second. The experiment is first in laboratory work. At times in clinical work there are unavoidable dilutions of the carbon dioxide mixture by additions of oxygen, anesthetic gases, aspirating of the patient, and looseness of fit of the face mask on the patient.
It is evident that the accuracy of the laboratory work would be greater than the clinical work. By comparing the results obtained under both conditions, it has been found that the laboratory results are the more accurate of the two. Regardless of how nearly the same the laboratory test apparatus and the clinical conditions are, however, it is not possible to learn all the things by laboratory procedure that were found clinically.

For example, the time of life of the absorbent could not be predicted from laboratory results. Variations in carbon dioxide expired by the patient could not be forecast. Effects of dilutions and operations upon the test could not be predetermined and many other factors could not be foreseen by laboratory procedure.

**TABLE 1**

**Comparison of Differences between Laboratory Tests and Clinical Results**

<table>
<thead>
<tr>
<th>Wt. of Sample in Gm.</th>
<th>Time in Minutes to 0.6% CO₂</th>
<th>Average % CO₂ Expired</th>
<th>Rate of Flow of CO₂ in cc./min.</th>
<th>Rate of Flow of CO₂—O₂ in cc./min.</th>
<th>Total Vol. of CO₂ to 0.6% CO₂ in cc.</th>
<th>Total Vol. of CO₂—O₂ to 0.6% CO₂ in cc.</th>
<th>WL of CO₂ in Gm. Picked up to 0.6% CO₂</th>
<th>Per cent of Theoretical Ca(OH)₂ Unused (calculation based on 100% Ca(OH)₂)</th>
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</thead>
<tbody>
<tr>
<td>Clinical Data—Baralyme—Curve “F”</td>
<td></td>
<td></td>
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<tr>
<td>669</td>
<td>284</td>
<td>3.33%</td>
<td>348.1</td>
<td>10,140</td>
<td>98,000</td>
<td>2,963,200</td>
<td>185</td>
<td>53.5%</td>
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<tr>
<td>60.1</td>
<td>231</td>
<td>4%</td>
<td>20.9</td>
<td>522</td>
<td>4,828</td>
<td>120,700</td>
<td>9.03</td>
<td>74.7%</td>
</tr>
<tr>
<td>Clinical Data—“High Moisture” Soda Lime—Curve “D”</td>
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<tr>
<td>636</td>
<td>344</td>
<td>2.7%</td>
<td>284.5</td>
<td>10,510</td>
<td>97,880</td>
<td>3,618,000</td>
<td>183</td>
<td>51.6%</td>
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</tr>
<tr>
<td>60.1</td>
<td>207</td>
<td>4%</td>
<td>23.2</td>
<td>580</td>
<td>4,800</td>
<td>120,000</td>
<td>8.97</td>
<td>74.8%</td>
</tr>
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</table>

**Notes.—** Curve “F” (Plate 14), it will be noted, has been added to the list of accurate ones used for comparison. Lobectomies and decortications usually resulted in curves with inaccurate data and therefore this curve was classified with the experimental ones originally. Since then it has been possible to check the sample used in this curve in the laboratory and it was found that the curve could be included with those for accurate comparison. This curve serves as a good illustration that the time of life of the absorbent is no value for use in comparing various curves. Although in curve “F” the total time to 0.6 per cent carbon dioxide is shorter (195 min.) than the total time in curve “F” (284 min.), more carbon dioxide (101,900) is picked up to this point in curve “F” than is picked up (98,900) in curve “F.”

The curves discussed in this work are “A,” “B,” “C,” “D,” “E,” “F,” “H,” “I,” “N,” “P,” and “Y.”

The “regeneration” theory for the return of activity of soda lime states that the return of activity is the result of the interaction of sodium carbonate
with calcium hydroxide to regenerate the more active and soluble sodium hydroxide. It is a chemical fact that the reaction in solution in water of sodium carbonate with calcium hydroxide yields insoluble calcium carbonate and soluble sodium hydroxide. In discussing the so-called "regeneration" theory of exchange between sodium carbonate and calcium hydroxide further, the following facts help to illustrate that if this exchange does take place, it is not the true reason for revivification of spent soda lime, as had been stated.

In chemistry it is a well-known fact that sodium hydroxide is classified as an active base. Calcium and barium hydroxides are classified as moderately active bases. Activity may be stated as the avidity with which a chemical will react.

The avidity with which sodium hydroxide reacts with carbon dioxide is greater than that of calcium hydroxide and barium hydroxide. The reaction is 

\[ 2Na\text{OH}_2 + H_2\text{CO}_3 \rightarrow Na_2\text{CO}_3 + 2H_2O \]

A factor contributing to the avidity of the reaction of sodium hydroxide with carbonic acid to form sodium carbonate and water is the solubility of the end product, sodium carbonate.

The avidity of the reaction of calcium hydroxide and barium hydroxide to form their carbonates is not as great as sodium hydroxide. Carbonates of both these hydroxides are very insoluble and an exchange between barium carbonate and calcium hydroxide as in the following equation 

\[ Ba\text{CO}_3 + Ca(\text{OH})_2 \rightarrow Ca\text{CO}_3 + Ba(OH)_2 \]

is a very remote possibility. However, baralyme analyzing 20 per cent Ba(OH)\(_2\)·8 H\(_2\)O and 80 per cent Ca(OH)\(_2\) gives a better absorbent life than a "high moisture" soda lime (15 per cent moisture content—2.5 per cent sodium hydroxide and 97.5 per cent calcium hydroxide content). This proves further that it is the sufficient and constant moisture content that promotes the reaction with calcium hydroxide.

To prove this point more completely, a mixture of calcium hydroxide and 18 per cent water was made and broken into particles of the same mesh size as "high moisture" soda lime. On testing this mixture, both clinically and in the laboratory, the lime with 18 per cent moisture content gave very efficient absorption of carbon dioxide without the presence of sodium hydroxide.

It is evident that the "regeneration" theory is not the answer for renewed activity of "low moisture" soda lime after "peaking," nor is sodium hydroxide needed to give efficient absorption of carbon dioxide by calcium hydroxide. Moisture is the essential propagating agent and only in the form of a hydrate can its permanent presence be assured.

REFERENCES

This report is the result of investigations conducted during 1945 at Walter Reed General Hospital, Washington, D. C.

Full credit is given to Mr. L. J. Nuhn for his painstaking efforts and cooperation in conducting chemical analyses and compiling the statistics for this study.