FACTORS AFFECTING THE PERFORMANCE OF ABSORBENTS

ELWYN S. BROWN, M.D.

TESTS of commercial absorbents by a continuous flow of gas through to-and-fro canisters indicated that a maximum effective carbon dioxide absorption capacity of 15 to 20 liters per 100 grams of soda lime could be expected.[1] However, the breathing patterns of anesthetized patients have discontinuous and irregular gas flow. The effective capacity with such varied flow patterns could be quite different from the capacity found for a continuous flow of this same average or mean flow rate. It has been supposed that the static conditions prevailing in the canister during part of the respiratory cycle in the circle may lengthen absorbent life by allowing some regeneration. On the other hand, overloading the canister with a tidal volume exceeding the void space could reduce absorbent life.

The object of this study was to examine the effect of variations in breathing pattern on the effective absorption capacity of absorbents. With this information, the safety factors pertinent to the design of absorbers are determined.

METHODS

A mechanical ventilation analogue[2] was employed as a test subject to provide values in respiratory parameters not frequently maintained clinically for prolonged periods of time. A part of the dead space of the mechanical ventilation analogue was replaced by an infrared CO_2 gas analyzer and a pneumotachograph. Input CO_2 rate, respiratory rate, and functional residual volume were adjusted to the desired values. The circle absorber charged with absorbent was attached and the tidal volume adjusted. The absorber was disconnected; fresh absorbent was weighed into the canister; and the absorber was reconnected to the analogue. All studies involved a closed circle system.

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A slow continuous recording of CO_2 concentration and flow rate was made. Total volume of CO_2 admitted to the analogue was read from a calibrated dry gas meter. Readings were taken every half hour during the test. CO_2 input rate was monitored and adjustments made to maintain CO_2 production rate within 3 per cent of the desired rate.

The pneumotachograph and CO_2 analyzer were calibrated before and after each test. The CO_2 base line was checked by disconnecting the absorber hourly to allow the analogue to inspire room air.

The soda lime used in these studies was Soda Sorb of the same lot that had shown a maximum effective absorption capacity of 16 l./100 Gm.[1] Baralyme pellets with a maximum effective capacity of 10 l./100 Gm. provided a contrasting absorbent with low activity and capacity. Since the capacity of both absorbents have subsequently been improved, the data presented is intended only for illustration of principles.

Several pitfalls beset such a study as this. For example, the Heidbrink 9B at first showed a five hour time efficiency for the first chamber with average test conditions. However, the second chamber failed in less than an hour. In further studies of this absorber and of the Foregger CF No. 2 which has parallel canisters, the opening to the parallel canister was sealed to prevent cross leaks. Leaks through bypass valves were also observed. Replacement of the one-way valves was often necessary to reduce initial inspired CO_2 concentration below 0.5 per cent in the Foregger CF No. 1 and No. 2 which were fitted with Sadd or Henderson-Haagard valves in the circle system tested.

RESULTS

At test conditions which correspond to the values in the average adult patient (500 cc. tidal volume, respiratory rate of 15 per minute, and a CO_2 production of 280 cc. per

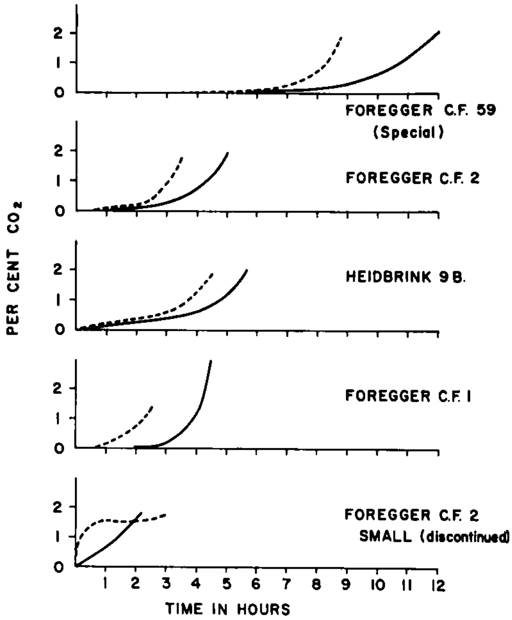

FIG. 1. Time efficiency curves for average respiration. Tidal volume 500 cc., rate 15 per minute, carbon dioxide input 280 cc. per minute. Dashed lines, Baralyme pellets; solid lines, Soda Sorb.

minute), efficiency in relation to time was directly related to the quantity of absorbent an absorber held (fig. 1). The Heidbrink 9B Foregger CF No. 1, and the CF No. 2 (large)* all had about the same time efficiency: 3½ hours to an end point of 0.5 per cent when soda lime was the absorbent. Variation in time efficiency was ± 5 per cent when test conditions were duplicated.

The rate of the terminal failure was different for each of these absorbers. In the Foregger CF No. 1, failure was rapid; the inspired CO_2 concentration rose from 0.5 per cent to 1.0 per cent in less than half an hour. This terminal rise in concentration of inspired CO_2 required considerably more than half an hour with other absorbers.

The time efficiency was shortened one to two hours when Baralyme pellets were the absorbent. The Heidbrink 9B had an efficiency rating of 3 hours, the Foregger CF No. 2 (large) 2½ hours, and the Foregger CF No. 1 two hours to an end point of 0.5 per cent CO_2. Terminal failure was rapid with 1 per cent CO_2 being reached in about half an hour in each case. The Foregger CF No. 2 (small) failed within a few minutes with Baralyme pellets. However, the absorber maintained an exit concentration of 1.5 per cent CO_2 for over two hours before an additional rise in inspired CO_2 occurred.

Increasing the tidal volume and reducing respiratory rate decreased efficiency by one-half to two hours when tidal volume was increased from 500 cc. to 750 cc. (fig. 2). Little or no further reduction in efficiency resulted when tidal volume was increased to 970 cc. CO_2 input rate was increased from 280 cc. to 330 cc. per minute to maintain a normal CO_2 tension in the expired air at the slower respiratory rates and larger tidal volumes.

Increasing the tidal volume and CO_2 input rate while maintaining a respiratory rate of 15 per minute and a normal CO_2 tension, a significant reduction in time efficiency was observed (fig. 3). This decrease in time efficiency was proportional to the increase in CO_2 production rate. For the Foregger CF No. 1 and CF No. 2 (large) failure occurred within minutes at the highest CO_2 input of

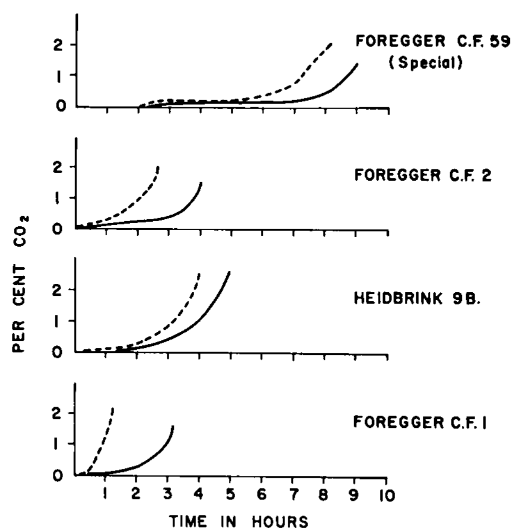

FIG. 2. Time efficiency curves with slowed respiration. Tidal volume 750 cc., rate 10 per minute, carbon dioxide input 310 cc. per minute. Dashed lines, Baralyme pellets; solid lines, Soda Sorb.

* These absorbers designed by Adriani for pediatric anesthesia originally had canisters holding 300 grams of lime. Subsequently, the canisters were enlarged to hold 450 grams of lime.

650 cc. per minute (fig. 4). The CO_2 concentration in inspired air rose within a few breaths to reach a high concentration where it remained until terminal failure. This result parallels the effects seen with Baralyme pellets in the CF No. 2 (small) with a production rate of 280 cc. per minute and tidal volume of 500 cc.

When the same data are analyzed to obtain the effective capacity, the effect of increasing tidal volume is again found to be minimal with active absorbent (table 1). As long as minute volume remained at 7.5 liters per minute, the effective capacity was about 14 liters of CO_2 per 100 grams for soda lime, which compares favorably with the maximum effective capacity of 16 liters per 100 grams.[1] When minute volume was doubled, the smallest canister (400 cc. volume) had no effective capacity. On the other hand, the largest canister (1320 cc. volume) was relatively unaffected. Intermediate sized canisters showed some decrease when minute volume was doubled but little change when the minute volume was increased only 50 per cent.

Baralyme pellets had an effective capacity of about 10 liters of CO_2 per 100 grams in the largest absorber. This is equal to the maximum effective capacity of 10 l./100 Gm.[1] In the smaller absorbers, an increase in tidal volume alone was detrimental, as was an increase in minute volume.

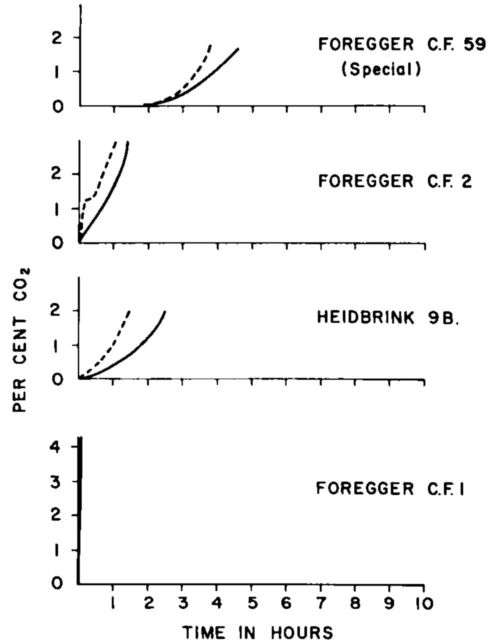

FIG. 4. Time efficiency curves with grossly increased carbon dioxide production. Tidal volume 970 cc., rate 15 per minute, carbon dioxide input 650 cc. per minute. Time efficiency was considerably reduced for all canisters; the 1200 gram canister failed in four hours. Dashed lines, Baralyme pellets; solid lines, Soda Sorb.

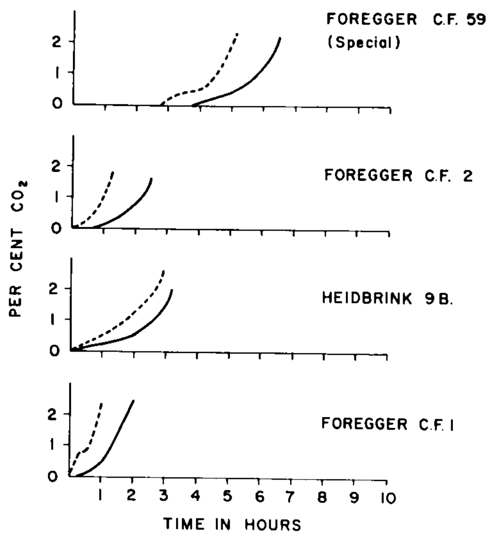

FIG. 3. Time efficiency curves with increased carbon dioxide production. Tidal volume 750 cc., rate 15 per minute, carbon dioxide input 480 cc. per minute. A marked decrease in time efficiency results from the added load. Dashed lines, Baralyme pellets; solid lines, Soda Sorb.

The Heidbrink 9B absorber showed a reduced efficiency with an effective capacity of only 11 liters of CO_2 per 100 grams for soda lime. This is about 75 per cent of the effective capacity found for the other three absorbers. The effective capacity when utilizing Baralyme pellets was also reduced to the same degree.

Discussion

These studies confirm previous determinations of the maximum effective absorption capacity of absorbents using continuous flow techniques through circle absorbers.[1] The effective capacity of 14 l./100 Gm. was slightly less than the maximum effective capacity of 16 l./100 Gm. for the soda lime because an end point of 1 per cent CO_2 in inspired gas was employed. Changes in tidal volume and

TABLE 1

Time Efficiency of Circle Absorbers

	T.V.	R.R.	Alveolar CO_2 %	CO_2 Input cc./min.	Absorbent Wt.	Endpoint 0.5% CO_2		Endpoint 1% CO_2	
						Time	l./100 Gm.	Time	l./100 Gm.
Foregger CF No. 2 (Large)									
Soda Lime	500	15	5.18	272	500	216	11.8	255	13.9
	750	10	5.3	318	480	198	13.1	227	15.0
	970	7.75	4.93	312	480	159	10.3	222	14.4
	750	15	5.34	480	487	106	10.5	134	13.2
	970	15	5.05	622	512	15	1.8	40	4.9
Baralyme	500	15	5.32	279	570	147	7.2	184	9.0
	750	10	5.15	308	553	93	5.2	122	6.8
	970	7.75	4.74	300	541	84	4.6	103	5.7
	750	15	5.37	484	550	38	3.3	55	4.8
	970	15	5.15	635	548	2	0.2	5	0.6
Foregger CF No. 1									
Soda Lime	500	15	5.25	276	400	209	14.4	234	16.1
	750	10	5.27	316	390	164	13.3	176	14.3
	970	7.75	5.27	334	390	140	12.0	164	14.0
	750	15	5.34	482	423	85	9.7	103	11.7
	970	15	5.3	652	400	>1	—	>1	—
Baralyme	500	15	5.37	282	442	108	6.9	132	8.4
	750	10	5.5	330	448	43	3.2	54	4.0
	970	7.75	5.29	335	440	36	2.7	51	3.9
	750	15	5.4	486	448	10	1.1	42	4.5
	970	15	5.3	652	445	>1	—	>1	—
Heidbrink 9-B									
Soda Lime	500	15	5.43	288	747	210	8.1	285	11.0
	750	10	5.36	322	752	201	8.6	237	10.1
	970	7.75	5.23	331	725	195	8.9	240	10.9
	750	15	5.28	475	750	120	7.6	157	10.0
	870	15	5.27	650	742	66	5.8	105	9.2
Baralyme	500	15	5.23	275	812	162	5.5	222	7.5
	750	10	5.3	318	822	158	6.1	187	7.2
	970	7.75	5.3	336	830	120	4.9	193	7.8
	750	15	5.25	473	823	60	3.4	99	5.7
	970	15	5.3	652	841	40	3.1	61	4.7
Foregger CF No. 59 (Special) and Kirchhof Valve									
Soda Lime	500	15	5.35	281	1250	570	12.8	636	14.3
	750	10	5.27	316	1200	450	11.8	516	13.6
	970	7.75	5.19	332	1200	450	12.5	508	14.0
	750	15	5.25	473	1203	312	12.2	348	13.7
	970	15	5.34	658	1203	192	10.5	235	12.8
Baralyme	500	15	5.25	276	1325	450	9.4	494	10.3
	750	10	5.3	318	1322	375	9.0	435	10.4
	970	7.75	5.33	337	1330	285	7.2	350	8.9
	750	15	5.31	478	1320	243	8.8	270	9.8
	970	15	5.3	652	1379	180	8.5	203	9.6

T.V. = tidal volume; R.R. = respiratory rate.

rate had relatively little effect on the effective capacity in the largest absorber. In the smaller absorbers, however, a reduction in the effective absorption capacity occurred with changes in breathing pattern.

The effects of changes in breathing pattern on the effective absorption capacity of a given volume of absorbent are best analyzed in relation to the active zone of absorption which has been called the "absorption wave." During the flow of expired air through the absorbent bed, a CO_2 concentration front is produced. This concentration front will vary in shape and length as the instanteous flow rate through the absorbent varies. In a small canister, high peak flow rates and large tidal volumes can extend this front through and beyond the absorbent bed. As the flow of expired air slows and stops, the concentration front recedes toward the canister inlet. If enough time elapses between periods of flow, all the gas in contact with absorbent can be freed of CO_2 during this pause. However, if the pause is not long enough or the absorbent at the inlet is too exhausted, some CO_2 remains in the gas near the inlet.

Since the absorption rate depends on the CO_2 concentration, the greatest amount of CO_2 will be absorbed by the first absorbent encountered by expired air. As a consequence, this absorbent is the first to be exhausted. With almost complete exhaustion of absorbent at the inlet (indicator color change), expired air loses little if any of its CO_2 until it has passed beyond this exhausted absorbent. Thus, the absorbent bed has been reduced in its effective length or volume and the absorption wave penetrates that much further into the bed. This reduction in effective length of absorbent bed continues during exhaustion and eventually the concentration front reaches the end of the canister.

When the CO_2 concentration front goes beyond the end of the canister during the peak flow rate, a fraction of the tidal volume will carry CO_2 into the inspired gas. As exhaustion proceeds, the volume and CO_2 concentration of this fraction of the tidal volume increases. Eventually, none of the expired air can be completely freed of CO_2 during the pause while inspiration is occurring. From this point on failure of the canister is very rapid.

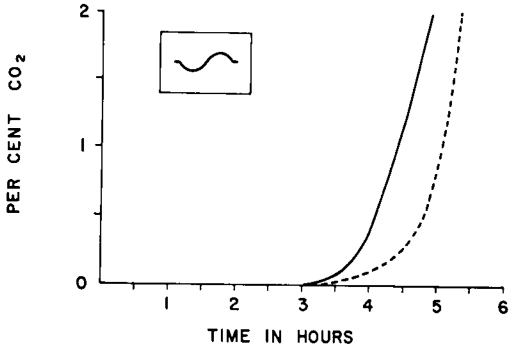

FIG. 5. Time efficiency curve showing minimum and maximum CO_2 concentrations in gas leaving the canister during exhaustion. Inset shows the recorded pattern of carbon dioxide concentration in gas leaving the canister after break-through starts. Dotted curve plots minimum and solid curve represents peak concentration.

These two fractions are readily observed in the gas leaving the absorbent by rapid continuous sampling of gas just at the end of the canister. Initially, if the absorber is not overloaded, the CO_2 concentration in the exit gas is zero throughout the respiratory cycle. The first evidence of failure is a sinusoidal wave of CO_2 during expiration. The CO_2 concentration is elevated during inspiration when flow has ceased and drops to zero at the start of expiration. During the remainder of expiration, the CO_2 concentration rises to a peak and then decreases slightly as flow decreases. As time passes, the peak gets higher and eventually in terminal failure the CO_2 concentration fails to fall to zero at the start of expiration. This sequence has been plotted in figure 5 where the CO_2 concentrations for the peak and the minimum are plotted during exhaustion of the canister.

The concept of peak flow rate determining how far the absorption wave penetrates the absorbent bed explains the lack of change in either time efficiency or effective absorption capacity with changes in tidal volume at a constant minute volume for soda lime. By reducing the respiratory rate as tidal volume was increased, the peak flow rate was held essentially constant. The length of the absorption wave was therefore the same, and the breakthrough of CO_2 occurred when exhaustion of the canister had proceeded to about the same extent for all three tidal volumes.

Baralyme pellets which had both a lower initial activity and a smaller effective absorption capacity had a reduction in absorption capacity with increased tidal volumes at constant minute volume. The volume of the absorption wave for this absorbent was calculated to be about 500 cc. for the minute volume of 7.5 liters. This exceeds the capacity of the CF No. 1 and is only slightly less than the volume of the CF No. 2. In these canisters, a stable absorption pattern could not be established before breakthrough of CO_2 occurred. Once breakthrough occurred, the large tidal volume carried considerable CO_2 through during the peak flow rate. Therefore, the end point was reached earlier and time efficiency and absorption capacity suffered.

Increasing peak flow rate without changing tidal volume was detrimental to effective absorption capacity. Only minor decreases in absorption capacity were found in the largest absorber and for 750 cc. tidal volumes in soda lime. The decreases were large in the smaller absorbers for 970 cc. tidal volumes. These large decreases were a result of the immediate breakthrough of CO_2 at the high peak flow rates. The large tidal volume relative to the absorber void space carried CO_2 into the inspired air during most of the expiratory cycle and failure was accelerated. Where the decreases were small, the absorption wave was contained in the absorber volume. Absorption could proceed for a considerable time before breakthrough occurred.

The increased CO_2 production rate that accompanied the increased peak flow rates probably had little effect on the absorption capacity but decreased the time efficiency considerably. The time efficiency should be considered as the quotient of effective absorption capacity and CO_2 production rate. Either a reduction in effective absorption capacity or an increased CO_2 production adversely affects the time efficiency. Thus, the decreases in effective absorption capacity produce a corresponding reduction in time efficiency that is superimposed on the effect of increased CO_2 production.

From these studies, the high peak flow rates associated with tidal volumes of a liter or more seen in a patient receiving meperidine and nitrous oxide anesthesia should most rapidly exhaust an absorber. To provide for such respiratory patterns requires a large volume of absorbent since the absorption wave would encompass at least 500 cc. of absorbent. In addition, a tidal volume of a liter could only be contained in about 2000 cc. of absorbent.[3] Since good efficiency is obtained in a canister of 1320 cc. volume for tidals of a liter, equally good or better efficiency can be expected with an absorber designed to accommodate a one-liter tidal volume.

Summary

Efficiency of CO_2 absorbent utilization was investigated by varying tidal volume, respiratory rate, and canister size. Efficiency was adversely affected by increased peak flow rates, by decreased absorbent activity, by increased tidal volume, and by channeling. These effects may explained in terms of the absorption wave, the zone where absorbent is most actively absorbing CO_2. Increased peak flow rate and decreased absorbent activity increase the amount of absorbent involved in the absorption wave. In small canisters, increasing the tidal volume hastens terminal failure which begins when the absorption wave at the peak flow rate spills out the end of the absorbent bed. Larger canisters were less affected since the absorption wave always encompasses a smaller fraction of their absorbent bed. As expected, the life of the absorbent was inversely proportional to the CO_2 input rate in a canister of adequate dimensions.

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REFERENCES

1. Brown, E. S.: Performance of Absorbents: Continuous Flow, Anesthesiology **20**: 41 (Jan.-Feb.) 1959.
2. Elam, J. O., Brown, E. S., and Elder, J. D., Jr.: A Mechanical Ventilation Analogue, U.S.A.F. School of Aviation Medicine, Unnumbered Report (May) 1954.
3. Brown, E. S.: Voids, Pores, and Total Air Space of Carbon Dioxide Absorbents, Anesthesiology **19**: 1 (Jan.-Feb.) 1958.