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NEW ASPECTS OF CARBON DIOXIDE ABSORPTION IN ANESTHETIC CIRCUIT

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1. Preface

The improvement of carbon dioxide absorbents and of anesthetic apparatus as well have contributed much to the practice of anesthesia towards its safety and security. Modern anesthetic apparatuses provide a fine and wide range control of oxygen and anesthetic gas concentrations, but they fail to facilitate the adequate control of carbon dioxide concentration in the circuit. For the proper elimination of carbon dioxide from the gas mixture to be rebreathed, we can rely clinically only on rather rough criteria, in spite of the important influences of inhaled carbon dioxide concentration on the patient's physiology. We are therefore obliged to take attentive and constant care for proper elimination of carbon dioxide from the anesthetic system in our daily practice.

There are still many unknown factors in this subject, and obsolete ideas and mistakes continue to be advocated; even in some of the recently published books on anesthesia. The author will revise several aspects pertinent to carbon dioxide absorption in anesthetic circuits, so that they may be rationally and advantageously applied in our field of practice.

Chemical reaction and thermotics in carbon dioxide absorption by soda lime 2.

The chemical reactions of carbon dioxide absorption by soda lime can be expressed by the following formulae.

- 1) $CO_{4}+H_{4}O\rightarrow H_{4}CO_{4}$
- 2) $H_2CO_3 + 2NaOH$ (or 2KOH) $\rightarrow Na_2CO_3$ (or K_2CO_3) + 2H₂O
- 3) Na_2CO_3 (or K_2CO_3)+Ca(OH)₂ \rightarrow CaCO₃+2NaOH (or 2KOH)

Most of the current products of soda lime contain potassium hydroxide, as well as sodium hydroxide, to activate the reaction. Some of them contain more of the former than the latter. All the reactions can be summarized as follows: $Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O$, *i.e.* one mole of carbon dioxide is absorbed to produce one mole of both calcium carbonate and water. At this moment, the heat as much as 27,500 calories is given off as the heat of neutralization. This neutralization reaction is of two gram-equivalents. Although the final production of water is only one mole, it is erroneous to understand that the heat production

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corresponds to one gram-equivalent. In fact, AINLEY-WALKER, using a Waters canister, obtained the value of approximately 118 calories per 100 cc. of carbon dioxide absorbed.¹⁾ This figure, well corresponding to the above, includes some amount of heat of adsorption and solution. In particular, the heat of adsorption is assumed to be relatively large according to the author's data.²⁾ On the other hand, the heat of ionization for one mole of carbonic acid is approximately minus ten thousand calories. It could be summarized that the heat generation for one mole of carbon dioxide absorbed equals almost to the heat of neutralization for two gram-equivalents, and such heat generation always occurs in proportion to the amount of carbon dioxide absorbed. Therefore, simple ideas commonly expressed such as "the less heat the absorbent generates, the better" are not always correct. Since current products of soda lime have relatively small proportion of sodium hydroxide and their initial moisture content is high enough, excessive heat production is avoided. Harm to the patient due to the inhalation of heated gas through the canister is improbable, since the amount of heat calculated from the specific heat of the gas and the heat of vaporization of water, is usually insignificant to affect the patient' body temperature, 1)3)4) though the condition may differ slightly with to-and-fro canisters.⁵⁾ Further grounds were given in AINLEY-WALKER's report on how the generated heat is disposed of. About one third of the total heat dissipates from the canister's surface, and approximately 30% is utilized in water evaporation while drying the absorbent and preventing its overheating. From 8% to 11% of the total heat is consumed for heating the gas, 11% to 12% for heating the absorbent, and about 5% for heating the canister.¹⁾

When the canister is hot to the touch, one may assume that the soda lime contained within is actively absorbing carbon dioxide. But this does not guarantee the full efficiency of absorption without any leakage of carbon dioxide. Cooling or replacement of canisters is not necessarily indicated simply because the canister has become hot.

3. CO_2 absorption activity and process of absorption by absorbents

There are a few terms to denote various aspects of CO_2 absorption activity of absorbents.⁶⁾⁷⁾ CO_2 absorption capacity represents the amount of CO_2 absorbed, and is usually expressed in relation to time. Fig. 1 shows the volume of CO_2 in milliliters absorbed by each specimen of Wakolime[®]* with various initial water content[†] ranging between 1.2% and 28.8% on wet basis during a period of 4 hours. The specimens weigh equally 5 grams when completely dry. When the initial

* Wako Pure Chemical Industries, Osaka, Japan.

[†] Water content or moisture of absorbents is usually expressed by the percentage of the diminished weight after 2 hours' drying at 105°C against the original weight of the specimen, e.g. α % on wet basis. Another expression is the percentage in which the denominator is the residual weight of specimen after the drying, e.g. β % on dry basis. The relationship between α and β is $\alpha = \frac{\beta \times 100}{100 + \beta}$, or $\beta = \frac{\alpha \times 100}{100 - \alpha}$.



Fig. 1. CO₂ absorption capacity of Wakolime, each specimen of dried 5 grams with various moisture; 1.2% (--○-), 6.8% (--⊗-), 11.8% (--□-), 18.5% (--∞-), 19.2% (-∞-), 20.4% (-∞-), 23.8% (-∞-) and 28.8% (-∞-) on wet basis. Abscissa: time in hours. Ordinate: absorbed CO₂ in milliliters which is humidified beforehand at the temperature between 20 and 30°C. N₂ ADSORBED (----) shows the volume of nitrogen in milliliters adsorbed by 5 grams of Wakolime. CO₂ absorbed by each of mono-, di- and tri-ethanolamine in 5 grams is shown by --∞--.

moisture is at its optimum, i.e. about 19%, the absorption reaches close to the peak within the first half an hour, and in fact exhibits approximately 90% of the theoretical maximum absorption capacity calculated from the chemical composition of the specimen. When the absorbent is less moist, absorption reaches a lower peak within a shorter period of time, suggesting that the exhaustion proceeds so much quicker. On the contrary, when the absorbent is more moist, it absorbs CO₂ more slowly, although the ultimate absorption capacity is not manifestly reduced. This phenomenon is more clearly seen in Figs. 2 and 3, which also show the effect of moisture on the CO₂ absorption capacities of Sodasorb®* and Wakolime during the first 15 minutes. Fig. 4 shows various curves of the absorption of Baralyme®** (barium hydroxide lime) with initial water contents ranging from 0% to 19.5%. The curves resemble those of soda lime with moisture of about 1.3 times of Baralyme, although the absorption capacity of Baralyme is smaller. Ethanolamines have much less absorption capacities than soda lime when compared in the same weight, and the absorption capacity decreases in the order of mono-, di- and tri- ethanolamine (Fig. 1). Anion exchange resins such as Dowex-3 and

* Dewey and Almy Chemical Co., Cambridge, Mass., U.S.A.

** Thomas A. Edison Industries, Stuyvesant Falls, New York, U.S.A.

Amberlite IR-4B have very poor CO_2 absorption capacities, apparently being of little value in anaesthesia. Addition of the water solution of ethanolamine to Wakolime impairs the absorption capacity probably by interfering with its porous structure (Fig. 2).



Fig. 2. Curves of CO₂ absorption capacity of Sodasorb up to 15 minutes. Twelve different specimens with various moisture between 0 and 28.4% on wet basis which are equally 5 grams in dried condition. Volume of ammonia in milliliters absorbed by dried 5 grams of soda lime with 16% moisture is expressed by NH₃ (--△--). Dotted lines show the absorption capacity of two ion exchange resins in 5 grams Dowex-3 (--×--) and Amberlite IR-4B (--▲--). Ethanolamine-added soda limes; 25% aqueous solution of mono-ethanolamine SL + H₂N·C₂H₄OH (·--·-), di-ethanolamine SL + HN·(C₂H₄OH)₂ (-----), tri-ethanolamine SL + N·(C₂H₄OH)₃ (-----), each of which is adjusted to make the moisture as 15% on wet basis.



Fig. 3. CO₂ absorption capacity of both 5 grams of Sodasorb[®] (---) and of Wakolime[®]
 (---) during the first one minute (▲), 5 minutes (*), 10 minutes (•) and 15 minutes
 (<). Abscissa: moisture content on wet basis. Ordinate: absorbed CO₂ in milliliters.



Fig. 4. CO₂ absorption capacity of Baralyme, each specimen of dried 5 grams with various moisture on wet basis; 0% (--○--), 4.5% (--◇--), 7.5% (--△-), 11.8% (--○--), 13.8% (--○--), 15.0% (--●--) and 19.5% (--▲-). Abscissa: time in hours. Ordinate: absorbed CO₂ in milliliters.

The absorption curve of 5 grams of Wakolime with 16% moisture for NH₃ gas, as shown in Fig. 2, is almost identical to that of sugar charcoal for the same gas.⁵⁾ Its shape also resembles the CO₂ absorption curves of the specimens with lower moisture (Sodasorb with 1.2% water content). These findings are explained by the SAMEJIMA's theory on the velocity of gas *sorption* by porous solids.⁸⁾⁹⁾ Continuous surface adsorption occurs in soda lime with relatively low moisture during the early stage of absorption, being expressed by the equation: $s \ln \frac{s}{s-x} - x = Kt$ (s: amount of adsorption at saturation, x: quantity of gas adsorbed at time t, and K: constant). With moderately moistened soda lime, this stage is followed by the late stage of internal absorption, expressed by another equation: $x=a \ln t+k$ (a and k: constants). The latter stage plays the main role in the reaction of specimens with moistures above 20% for their little surface adsorption. CO₂ absorption with moderately as a phenomenon of *sorption** or *chemisorption*.** Relations between moisture and absorption activity of soda lime granules will be further discussed in *Section* 6 in connection with their porous

Absorbents with various moisture, when they are exposed, in a shaking tank, to CO_2 containing gas whose concentration is controlled to be maintained at 5%, show suppressed absorption rates in general compared with when they are exposed to pure CO_2 . Wakolime with moisture in the vicinity of 7% exhibits the maximum CO_2 absorption capacity with the 5% CO_2 in oxygen, which nearly equals the capacity of the same specimen with 100% CO_2 . When the moisture increases to above 10%, the rate of absorption decreases, when the ambient CO_2 concentration is kept at 5%. This is probably due to the difference in pressure gradient of CO_2 and its relation to the water content.²⁾⁶

structure.

The effectiveness of the absorbent layer in removing CO_2 from the gas stream is referred to as CO_2 absorption efficiency or CO_2 absorption ratio, and is usually expressed by the percentage of removed CO_2 during the passage against the original CO_2 concentration. However, efficacious absorption is not only represented by the absorption ratio but also is confirmed by the acceptably low concentration of CO_2 which has leaked out of the absorbent-filled-canister, for which a range of up to 0.2-1.0% has been set by various authors...0.2%,¹² 0.4%,¹³ 0.5%,¹⁴⁾¹⁵⁾¹⁶⁾ 0.6%,¹⁷⁾ 0.7%¹⁸⁾ and 1% CO_2 .¹⁹⁾ These discrepancies are due to the difference in appreciating the safety threshold of CO_2 concentration,*** in the interpretation of

- * Sorption is the term applied for the combined process of adsorption and absorption. The gas in contact with solid material is adsorbed at the surface and simultaneously absorbed into the material to form a solid solution or a chemical compound¹⁰).
- ** Chemisorption or activated adsorption is one of the types of adsorption, where adsorbed molecules are held to the surface of solid by the bonds comparable to those in chemical compounds. The heat of adsorption in this type is greater than in another type of adsorption, *i.e. physical* adsorption or van der Waals adsorption¹¹.
- *** In the field of hygiene, the maximum permissible concentration of CO_2 is generally accepted as around 0.1%, while CO_2 in the atomospheric air is $0.03 \sim 0.04\%$.

recorded CO_2 data which fluctuates with respiratory cycles, in the sampling method, etc.⁶⁾²⁰⁾. There has also been a confusion in judging the adequacy of a canister just by the safety threshold of CO_2 in the *inhaled* gas instead of by the acceptability of CO_2 *immediately after* passing through the canister. Of course, optimum acceptability and safety threshold are not one and the same thing, and no absorber *per se* can be too efficient.

By analyzing E.S. BROWN's experiment on the activity of absorbents,²¹⁾ one can assess how CO₂ absorption efficiency is affected by the gas-absorbent contact time. He passed a constant flow of 5% CO₂ in oxygen with saturated humidity, using different flow rates, through various canisters packed with fresh soda lime, and observed the CO₂ concentration at the outlet of canisters. Now, the relation between the absorption ratio (y%) and the gas-absorbent contact time (t seconds) are expressed by an equation; $y=100\left(1-\frac{1}{\alpha^{kt}}\right) \div 100\left(1-\frac{1}{4^{10t}}\right)$. It is seen that 0.1, 0.12, 0.16, 0.2, and 0.3 second is required for absorbing 75%, 80%, 90%, 94%, and 98% of the original CO₂ concentration, respectively. If the contact time is longer, the absorption comes closer to perfection, although several ten p.p.m. of CO₂ inevitably leaks from the canister. While actually inspired CO₂ concentration is influenced by many other factors, keeping the CO₂ at the exit of canister as low as possible is mandatory.

Dynamic aspects of CO_2 absorption are further disclosed by the following experiments, using intermittent flows through the layers of soda lime in a canister.



Fig. 5. Diagram of the experimental apparatus. (For explanation see text.)

Continuous sampling is made from various levels of the packed absorbent (1, 3, 5, ..., 15, 20 cm. above the bottom), and CO_2 concentration is recorded using an infrared CO_2 analyzer and a two-channelled recorder. Various types of intermittent flow of 4.6–5.0% CO_2 in oxygen is pumped upwards through the canister by a Bennett BA-4 Anesthesia Ventilator, and simultaneous recording of the flow velocity is made using a pneumotachograph (Fig. 5). For the variety of ventilatory patterns, conditions are provided by the ventilator in the following ranges; flow velocity (peak flow rate): 0–1500 cc/sec., tidal volume (stroke from the ventilator): 300–1500 cc., frequency: 5–30 times per minute, minute volume: 3–15 l/min., and pause: 0.5–5 seconds.²²)

The influence of ventilatory factors on the dynamics of CO_2 absorption is demonstrated by comparing the fluctuation of CO_2 concentration, while altering the ventilatory patterns. In Fig. 6, two different ventilatory patterns are compared while the upper and lower limits of CO_2 fluctuations are continuously recorded at different levels in a canister. Flow velocity, stroke-pause ratio, and tidal volume are fixed, but the condition **A** has tidal volume of 400 cc. and frequency of 24 per minute, and the condition **B** has tidal volume of 800 cc. and frequency of 12 per minute. Except at the level of 1 cm. above the bottom, **B** consistently gives higher



Fig. 6. Comparison of CO₂ concentration at different levels of absorbent layers (1, 5, 10 cm from the bottom) under two different ventilatory conditions.

B: tidal volume 800 cc, frequency 12/min., stroke: pause=1:4 (1 sec.: 4 sec.), upper limit — — — — and lower limit \neg — \neg \neg of CO₂ %. In either condition, flow velocity is 800 cc/sec. and minute volume is 9.6 *l*/min.

upper limit of CO₂ than A, while the lower limit in A is always higher than in B.

In Fig. 7, tidal volume and frequency are fixed, and the flow velocity in D doubles that in C. D results in remarkably higher CO_2 concentration than C at the upper limit, but renders lower CO_2 concentration than C at the lower limit since the pause in D is longer than in C.



Fig. 7. Comparison of CO₂ concentration at different levels of absorbent layers (1, 3, 5, 8, 10, 12 cm from the bottom) under two different ventilatory conditions.

C: flow velocity 360 cc/sec., stroke:pause = 1:2 (5/3 sec.: 10/3 sec.), upper limit — and lower limit $\overline{}$ of CO₂ %.

D: flow velocity 720 cc/sec., stroke:pause = 1:5 (5/6 sec.: 25/6 sec.), upper limit ---- and lower limit $\neg \neg \neg$ of CO₂ %. In either condition, tidal volume is 600 cc and frequency is 12/min.

When tidal volume and flow velocity assume those of **D** and frequency is increased to 1.5 times, accordingly increasing minute volume to 1.5 times, the upper limit of CO₂ fluctuation is only slightly elevated, whereas the lower limit is remarkably elevated and the deviation from the D curve is more marked according to the time.

The difference in the absorption pattern can be demonstrated more clearly by varying the ventilatory factors as flow velocity, tidal volume, pause, etc., every few cycles of the ventilation in a single course of the similar experiment. On the left side half of Fig. 8, fluctuations of CO2 concentration are recorded when minute volume and pause are kept constant while frequency and accordingly tidal volume are altered stepwise within a short limited time to avoid the influence of the absorbent exhaustion. In this manner the changes in flow velocity is reflected directly





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Fig. 8. Effects of flow rate (upper tracings) on carbon dioxide leakage (lower tracings).

Ventilatory condition.

(left)
٦	,

(right)

														_
	Fidal volume (cc.)	Rate /min.	Strok (T	(e : I atio)	Pause	Flow rate (cc/sec.)	T v	`idal olume (cc.)	Rate /min.	Stroke (sec.)	:	Pause (sec.)	Flow rate (cc/sec.)	-
Α	600	12	1	:	l	240	а	600	12	2.4	:	2.6	250	
В	480	15	3	:	5	320	b	600	12	1.2	:	3.8	500	
С	400	18	1	:	3	480	с	600	12	0.75	:	4.25	750	
D	360	20	1	:	5	720	d	600	12	0.6	:	4.4	1000	
ļ	Minute	volume	is 7.2	l/min	and a	the pause is	e	600	12	0.48	:	4.52	1250	
2.5 sec. thoughout the experiment. Hence the														
stroke is 2.5 sec. in A, 1.5 sec. in B, 5/6 sec.														
in	C and,	0.5 sec	:. in I	Э.		1								

 CO_2 concetration was detected at the depths of 6cm (left) and 3cm (right) from the bottom in each case,

 CO_2 concentration was detected at the depth of 5cm,

on the passing concentration of CO_2 . The upper limit of CO_2 concentration at the levels of detection is elevated with the increase of flow velocity. The lower limit of CO_2 concentration remains essentially unaltered. The right side half of Fig. 8 shows the CO_2 concentration at a level of detection in the canister when tidal volume and frequency are fixed and the duration of tidal inflow (stroke phase) is varied rendering five stepwise increases of flow rate with an increment of 250 cc/sec. Here is also shown a nearly linear or more accurately logarithmic relation between the peak flow rate and the upper limit of CO_2 concentration. In other words, the contact time (*i.e.* the reversal of flow rate) and the maximum concentration of passing CO_2 have an exponential relationship.

The relationship between the volume of demanded fresh absorbent layer for the complete absorption, *i.e.* absorption zone (v cc.) and the flow rate of CO₂containing tidal inflow (x l/min.) is also derived experimentally as $v \doteq \alpha x$ (α : constant in the range between 9 and 16), that is similar to the linear relationship postulated by BROWN in his experiment using continuous flows.²³⁾

The influence of tidal volume on the upper limit of concentration of passing CO_2 is not a significant one, if minute volume, flow rate, and stroke-pause ratio are fixed. The increase of tidal volume, with the decreased frequency in inverse proportion, appears to effect mainly to depress the lower limit of CO_2 concentration and to widen the amplitude of the fluctuation of passing CO_2 in a ventilatory cycle, but this is rather due to the result of concomittant prolongation of the pause. It could be concluded that the influence on the leakage of CO_2 of the change in tidal volume is not so predominant as that of the change in flow rate. The reason for this is considered that, as long as the front of every tidal inflow is cleared for CO_2 by the sufficiently quick absorption exerted by the fresh upstream layers of ab-

sorbent, the inter-absorbent space to be occupied by the tidal volume does not directly correlate with the CO₂ leakage.

When tidal volume and consequently minute volume are increased with fixed frequency and flow velocity, both the upper and the lower limits of fluctuating CO_2 concentration are elevated, since the minute volume containing a constant CO_2 concentration has the direct relation with the progress of exhaustion of the absorption capacity.

Detection of the influence of the pause can be achieved by fixing tidal volume and flow rate and decreasing the frequency so that the duration of pause is prolonged. This results in depressing the lower limit of the concentration of passing CO_2 . On the contrary, when tidal volume and frequency are varied while flow rate and pause are fixed, the lower limit of passing CO_2 concentration is maintained constant. Thus it is concluded that the lower limit of passing CO_2 concentration is under the direct control of the duration of pause.

From the above series of observations, the following aspects on CO_2 absorption in the canister can be set forth, to be comprehensive. Fig. 9 shows schematic diagrams of the fate of CO_2 during a tidal inflow of respiratory gas through a canister,











Fig. 9. Shematic diagrams showing CO₂ absorption patterns in relation to the size of canisters. (See text page 13)

C : Upper end of packed absorbent in canisters.

A: Upper end of required absorbent layers for complete CO₂ absorption (absorption zone).

T : Tidal front of inflowing gas occupying the air space of absorbent.

Upper three (M): $T \ge A$

- M_1 : C>A, where CO₂ absorption is completed within T, regardless of C>T₁>A or T₂ >C>A.
- M_2 : C < A, where C is too small to provide sufficient absorption zone, so that the amount of CO₂ represented by C-A leaks from the canister.
- M_3 : A > C, where the required zone for complete absorption extends over C, owing to, e. g., overbalanced peak flow rate and/or too moistened absorbent, permitting leakage of CO₂ as much as C-A.

Lower three $(N): T \le A$

- N_1 : C>T, where C is large enough to cover T, regardless of C>A₁ > T or A₂ > C>T.
- N_2 : C < T, where C is too small to cover T, permintting leakage of CO₂ as much as C-T.
- N_3 : T>C, where the required zone for complete absorption extends over C and even T, owing to, e.g., the gradual exhaustion of absorbent, permitting leakage of CO₂ as much as C-T.

On each rectangle, C is the upper end of packed absorbent layers. The width of dotted areas corresponds to the passing concentration of CO_2 during the upward movement of gas. The depth of the absorbent layer required for complete elimination of CO_2 from a tide of gas with a given volume and a peak flow rate is represented by the height of A. The front line which the tidal volume reaches in the canister is represented by T. The patterns of CO_2 absorption according to varieties of peak flow rates are well explained by the shape of dotted areas in relation to the heights of C and T. Naturally the dotted areas quickly ebb downwards during the pause.

The three upper diagrams represent a state when the tidal front T exceeds or equal to the absorption zone A (M), and the lower represent another state when the tidal front T is exceeded by A (N). The former state (M) is seen when the absorbent has enough or surplus activity for varieties of flow velocity so that whether CO_2 leaks from the canister depends primarily on the peak flow rate. The latter (N) occurs in such conditions when the activity of absorbent has become lowered or the flow velocity has overbalanced the tidal volume so that complete absorption is not achieved during the phase of tidal inflow and the front of tidal gas carries still unabsorbed CO_2 .

Assuming that tidal volume of inflowing gas is over 200 cc. and its peak flow rate is under 30 l/\min , the phase of tidal inflow has a duration longer than 0.4 second. This assures almost one hundred per cent absorption of CO₂ before the gas reaches its tidal front (T line), as long as soda lime remains fresh. In usual circumstances, the phase of tidal inflow lasts longer than the above condition. Besides, the upstream layers of absorbent which determine whether the efficiency of the canister is at its optimum or not must be maintaining its fresh activity. Therefore, the zone required for the complete absorption (up to A line) is usually

smaller than the zone occupied by tidal volume (up to T line), so that CO_2 starts to leak when the canister space fails to cover the A line (M₂), instead of the T line. Whether a canister is still effective or starts to leak CO_2 depends primarily on flow velocity but not on tidal volume (M₁~M₃).

The other state (N) occurs when the tide of inflowing gas has an extraordinarily small volume but rather a high flow rate, and consequently a very short duration of the inflowing phase, or when absorbents are over-moistened or exhausted, the CO_2 absorption velocity is lowered and the required zone for complete absorption is enlarged. Hence, the absorption zone exceeds the tidal front, which then becomes to be the primary factor in CO_2 leakage. However, such a case is seldom encountered practically before CO_2 starts to leak.

The discussion so far has been concentrated mainly on the inflowing phase of tidal exchange. Carbon dioxide which is left unabsorbed during the phase of tidal inflow at a given level of absorbent is eliminated during the subsequent phase of pause, and the lower limit of CO_2 concentration at the end of pause is under the direct influence of pause duration. Absorption of CO_2 takes place during the

phases of both tidal inflow and pause, and it is improper to take only the absorption during the pause into consideration as has been suggested by ADRIANI.²⁾²⁶⁾³⁰⁾ The canister efficiency may in a sense be expressed directly by the average concentration of CO_2 in the whole mass of gas after passing through the canister. However, when the average value of CO_2 becomes excessive, fairly high concentration of CO_2 must have already been leaking during the phase of tidal inflow as its upper limit of fluctuation, which is under the direct control of flow velocity. Consequently, peak flow rate of passing gas is the key to the efficiency problem of the canister.

It is absurd to expect further absorption, for the CO_2 having already leaked from the canister, during the subsequent period of pause. Differently, one may resort to the idea of persistently providing equal or surplus air space against a given tidal volume as definite means of CO_2 elimination—an illogical solution because he has ignored the presence of 'tidally and fluxionarily functioning' absorption zone. This thesis would be well exemplified by the following obvious facts; 1) even a small canister whose air space is exceeded by a tidal volume can maintain the complete absorption for a while, 2) at the point when tidal volume exceeds the air space, the leakage of CO_2 does not commence abruptly but always insidiously, 3) leakage of CO_2 increases with increase of the peak flow rate of tidal inflow in spite of an ample period of pause during the respiratory cycle. On the other hand, even if the pause is short, leakage of CO_2 decreases as the inflow slows down, *etc.* 4) A canister packed with absorbent granules of more than 8 mesh, *i.e.* smaller in size, shows a higher absorption efficiency in spite of its less air space.

All the descriptions and statements on the absorption have so far dealt with the pattern of intermittent and unidirectional flow through the canister placed in the circle system. The 'to-and-fro' system of CO2 absorption demands discussion in some detail here. The flow pattern through a to-and-fro canister differs from that of the circle system in that there is no steady advancement of the absorption zone with the exhaustion of absorbent, since the to-and-fro tide of respiratory gas, provided its volume is fixed, occupies a constant air space between the granules and the absorbent layers beyond the tidal front are never utilized. The most critical drawback in the to-and-fro canister is, as has been pointed out by TEN PAS et al.,20) that the exhausted proximal absorbent zone progressively increases the dead space effect. NUNN²⁴) described a classification of breathing circuits in which an example was illustrated applying a circle system between the patient and the to-and-fro canister for reducing the dead space. However, as long as the flow pattern in the canister remains 'to-and-fro', the dead space effect of the exhausted absorbent can not be avoided. TAKAOKA²⁵) tried to minimize this dead space effect by circulating a portion of gas in the canister by means of a fresh gas inlet functioning on the Venturi principle. This is able partially to render the system a character of circle system, while leaving the most of drawbacks of the to-and-fro system with no positive solution. To-and-fro canisters have some more disadvantages repeatedly quoted; 1) easy channeling, 2) inhalation of alkaline dust, 3) inhalation of heated

gas, 4) difficulty in holding the canister, etc. All these together with the primitive and undifferentiated pattern of gas flow through the canister inevitably accompany the drawbacks of to-and-fro system, and the grave and unsavable disadvantage is that all the absorbent layers in the to-and-fro canister can never be utilized evenly. Thus, the unidirectional flow for filtering CO₂ is superlative for the highest efficiency of absorption.

4. Size and shape of canisters

Table 1 shows the capacities, the contents of soda lime, and the air space of various canisters. Several canisters of large capacities have in these years become popular, some of which are divided into two or three compartments. Most of the currently marketed soda lime has the intergranular space (voids) of approximately 40-47% and the intragranular space (pores) of 8%-a total air space in round figures of 48-55%.²⁶⁾²⁷⁾²⁸⁾ Adriani once gave a larger estimate of about 70-80%

Manufact. & Designation	Compart-*) ment (cc)	Sodalime wt. (g)	Total ^{†)} Air Space (cc)	Use ft) "(hr)		
Foregger		· .				
Waters						
$450gm(8 \times 13)$	630	550	350	$2\frac{1}{2}-4$		
350gm	440	400	240	l — 2		
l 80gm	250	250	150			
90gm(Infant)	110	100	60			
CF No.1	440	400	240	$1\frac{1}{2}$ — 3		
CF No.2	540(×2)	480	300	2 3-1-2-		
CF No.3(Jumbo)	1000×2	870×2	0011	20 - 25		
Ohio Heidbrink						
9B	860(× 2)	750	470	$2\frac{1}{2} - 4$		
19 or 18	2440	2200	1340	25 — 35		
20 or 21	1500×2	2700	1560	24 - 28		
Dräger						
Romulus(Ia)	700	650	430	3 — 5		
Octavian(IIIa)	1000	850	600	8 10		
Boyle						
Mark 2	520	455	280	2 — 3		
Mark 3	1100×2	910×2	1200	20 – 27		
Acoma K.U.(TS-6)	1000×3	800×3	1550	30 - 35		
T.I. Wistman Jumbo	2000	1650	1200	18 - 25		
Mera Novus(disposable)	650	550	370	3 - 4		

Table 1; Size of various canisters.

Figures are approximate only.

- *) $\times 2$ or $\times 3$ denotes number of consisters in series(two-, three-chambered canister), while $(\times 2)$ indicates those for alternate use (dual canister).
- ^{†)} Total air space for two- or three-chambered canister represents the space including the two or three compartments in Series, whereas that for dlual canister shows the space in compartment of one side in use. The figure for voids can be obtained by the total air space minus its 15% value(=pores).
- (†) Average duration of utility for closed circuit in adult.

for the air space using the soda lime of those days in a Waters canister, and used this figure in relation with the tidal volume.²⁹⁾³⁰⁾ However, air space *per se* has apparently little relevance to the absorption efficiency of canisters as clarified in *Section* 3.

MUNEYUKI reported on the relation of size and time efficiency of canisters.¹⁸) In his model experiment using a closed circuit, when the soda lime content is more than 500 g., apparently there is available sufficient contact time between the absorbent and the gas flow to complete the absorption, and the time efficiency is increased by 1.8 hours for every increment of 100 g. of soda lime. But when the soda lime content is below 500 g., absorption becomes readily inefficient being affected directly by the peak flow rate, tidal volume, channeling effect, *etc*.

As the efficiency of a canister draws near its end, the remaining layer of still effective absorbent becomes solely responsible for whether the canister starts to pass CO_2 or not, under the concomitant influence of the ventilatory factors, although it is difficult to draw a clear border line between the exhausted and the still effective layers of absorbent. When the total volume of absorbent in a canister increases, the ratio of remaining effective absorbent at the end point of canister efficiency decreases in general, and the amount of still effective absorbent to be discarded becomes smaller in relation to the total amount of absorbent in the canister. At the same time the duration of effective absorption of larger canisters approximates more closely to the period of complete exhaustion of the maximum absorption capacity of the absorbent by the CO_2 load. On these accounts any reasonable increase in capacity of a canister is generally accompanied by gain in safety and economy.

On the other hand, an excessive increase in the volume may, during a long or repeated use, result in uneven distribution and partial accumulation of water and also in deterioration of the color indicator, ultimately leading to 'caking' of the canister content. These factors increase practical difficulty in detecting the end point of canister efficiency. Another factor which makes a change of canister desirable is a hygienic consideration. For example, tuberculosis bacilli survive even in the alkaline media of soda lime. In practice and in general, it is safe to change the canister for checking the inside every 6–8 hours' use. Selection of a canister of appropriate size will be determined by the number of cases and the length of time it is likely to be in use. It is pointed out that choosing a large canister is not always desirable, especially for short and infrequent uses.

Canisters having two^{31,32} [or three¹⁸] separate compartments are preferable, as the upstream one can be changed in order when its absorption capacity is fully exhausted and the other which is placed downstream still has enough efficiency (Fig. 10). Then, no parts of absorbent will be discarded before completely ex-



Fig. 10. Exhaustion and replacement of absorbent in a two-chambered canister in use. The order of exhaustion is from the white zone (fresh) to the diagonal zone (fully exhausted).

(a) Separable two chambers in series, the upper one '3' filled with fresh absorbent serves as reserve. (Heidbrink No. 21, Dräger III, Acoma PH-2)
(b) Reversible type canister with undivided two chambers. (Foregger CF-3, Boyle Mark 3)

hausted. Formerly, canisters were often placed in parallel and used alternatively (Table 1*), but the trend has changed to placing them in series, so that absorption continues in them without interruption. Many investigators are satisfied that "resting" a canister for a period does not prolong its total time of effective absorption and a long and safe absorption effect is obtained in a long-term use with the modern absorbents and canisters.⁷⁾¹³⁾¹⁴⁾¹⁵⁾¹⁶⁾¹⁷⁾¹⁸⁾¹⁹⁾³³⁾

5. Regeneration and Color Indication of Absorbents

While soda lime is "resting", NaOH and KOH regenerate fairly rapidly in the absorbent granules, so that the change of pH at the surface may become sufficient to restore the indicating color to its original. This can be misleading if it is not realized that the amount of regenerated base is very small. Very quickly after the start of re-use, exhaustion occurs reverting it to the pre-regeneration grade.⁷⁾¹⁹⁾²⁵ It is well known that the effect of such regeneration affords no appreciable improvement of the over-all life of soda lime in a circle absorber. It is also understood that the process of regeneration is constantly taking place, even while the soda lime is in use, but this is not revealed by the color because simultaneous exhaustion overcomes. The above remarks apply also to Baralyme in current use, since it too contains KOH.³⁴



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Fig. 11. Surface of absorbent granules magnified by a scanning electron microscope; (approximately, $\times 1000$, Bars of 1 cm length indicate 10μ) A: Sodasorb, B: Mallinckrodt Indicating Soda Lime, C: Wakolime, D: Baralyme, B': Mallinckrodt Indicating Soda Lime after CO₂ absorption, and D': Baralyme after CO₂ absorption. Thus it will be seen that color is not an absolutely dependable guide to the absorption capacity of soda lime; nevertheless, if understanding is exercised, it can still be a more practical guide than the unstained, which gives no indication at all. The following must be borne in mind when using a color indicator and interpreting its significance. 1) If the water content is excessive, absorption is poor yet the color does not change. 2) If the water-soluble stain becomes washed off and/or if ethyl violet is degraded by ultra-violet beams during a long use, advantages originally offered by the color are lessened, or even misleading. 3) The water solution of dye, sprayed or mixed during manufacture of the granules, is made in different concentrations (e.g. 0.02-0.2% ethyle violet solution). Moreover, the dye may be distributed unevenly since inner or sunken parts of the granules are less accessible.

Clayton yellow (pink to yellow) is mixed evenly throughout the soda lime granules giving them a uniform pink appearence. If the preparation becomes too wet, the color becomes more brightly pink but absorption is impaired. Mimoza-Z, which is contained in Baralyme in a combination with ethyl violet, works just in the same way. Stains which change the color at pH in the neighborhood of 12, such as titan yellow, tropeoline O, *etc.*, can be used as effective color indicators experimentally and clinically. The selection of a color indicator appears to be rather a matter of personal preference.

6. Porosity and moisture of absorbent granules

The structure of soda lime is known to be "porous" 26)27)28), but the detail has never been visualized. Optical microscopy with various degree of magnification has been tried for inspection of the configuration of soda lime granules, but this method has hardly been satisfactory for obtaining clear pictures. A scanning electron microscope has enabled us to magnify the geometrical topography of the surface structure of absorbent up to several ten thousands times without any special pre-treatment as replication or slicing except gold-coating in vacuum. The structure of soda lime granules consists of conglomerates of millions of fine irregular materials or particles of μ unit range, some part of which taking crystallike appearances. Innumerable holes and paths of various sizes in extremely ragged structure apparently act to increase the active surface of the material (Fig. 11). Each brand shows some different features. After absorbing CO₂, the granular surface changes its feature to somewhat coke-like appearance by developing many minor craters, and finally developes rhombic crystalls of CaCO₃³⁵⁾. The physical significance of active porous surface of absorbents may well be understood by the sorption theory as previously described.⁸⁾⁹⁾ A different approach to this problem was made by BROWN²¹⁾ who applied the mass transfer concept on the absorption velocity of CO₂ by soda lime and computed that the active surface must be more than 100 cm² for one ml. of its 4-8 mesh grnules, which, if not porous, would have the surface area of only 5-6 cm².

Thus, it is essential to increase the effective surface area of absorbent by way

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of porosity. Because of its porosity and moisture, soda lime absorbs various substances; nitrogen (Fig. 1), ammonia gas (Fig. 2), ether, halothane, methoxy-flurane vapors, *etc.*³⁶⁾ It is well known that trichlorethylene absorbed by heated alkali is degraded into neurotoxic substances as dichloracetylene and phosgene.⁷⁾³⁷⁾³⁸⁾

The relationship between porosity and water content of soda lime granules has been examined.²⁶⁾²⁷⁾²⁸⁾ Intergrnular space (voids), intragranular space (pores), weight and volume of Wakolime (moisture on dry basis 0-41%) were measured according to the method described by BROWN.²⁶⁾ Then, the granular density, the bulk density, and the specific gravity of the absorbent material were calculated. It was shown that the more moist the granules, the less the total air space, which finally is reduced to less than a half of the bulk volume.

The effect of granular water content on pores can be roughly expressed by a formula,

p = 28 - 0.8x

x: water content in per cent on dry basis,

p: volume of pores in cc. per 100 grams of dried Wakolime.

This denotes that the pores decrease linearly with increase of moisture and approximately 80% of the water in the granules is utilized to occupy the pores, while the rest of the water is absorbed by the absorbent material, which consequently swells up and lowers its specific gravity. When the pores are just fully occupied by water, the specific gravity and the granular density become identical (1.7–1.8 g./cc.). When the absorbent holds more water, namely x exceeds 35%, water gradually inundates the pores and the granules become apparently wet.

Excessive moisture of soda lime also influences the flow resistance. Wakolime with various grades of moisture between 0% and 25% on wet basis was packed in a same canister evenly and snugly and was tested for the flow resistance under various continuous flows of oxygen from 10 to 100 $l/min.^{28}$ It was revealed that the resistance varies little while the moisture remains below 20%. But, when the moisture reaches 25%, the absorbent yields a greater resistance of almost twice of that with moisture of 20%, because the voids are inundated with water. The effect of moisture on the CO2 absorption activity of absorbents needs some more discussion. The relationship between the initial water content of soda lime or barium hydroxide lime and their CO₂ absorption capacity has been shown in Figs. 1-4 in Section 3. During the first few minutes of absorption, there is little difference in the amount of absorbed CO2 between low and high moisture specimens. But, later, the activity of soda lime with lower initial moisture decreases more quickly and significantly. Those with initial moisture of between 15% and 20% on wet basis maintain satisfactory absorption activities for longer period of time, and they perform the optimum absorption as a whole. As the moisture exceeds 20%, soda lime becomes wet and deprived of its proper reactivity. The speed of CO_2 absorption decreases with lessening of the active surface area as the granular pores are covered or filled with water. This fact also applies in explaining why

ethanolamine solutions added to soda lime granules to make the initial moisture 15% impairs the absorption activity (Fig. 2), although this was originally designed to enhance the absorption activity by the additive effect of both ethanolamine and soda lime. The effect of pores is readily blocked by the ethanolamine solutions. The water of hydration in Baralyme, whose optimum water content (11%-14%) on wet basis) is lower than that of soda lime (Fig. 4), has some merit in stabilizing the moisture owing to the water of crystalization of Ba(OH) \cdot 8H₂O,^{7)13)34)39)40) but still more amount of free water must be added for the maintenance of its optimum activity.}

Drying of soda lime granules occurs readily with practical significance. On exposing to the open air of room condition, fresh soda lime granules loose more than a half of the initial moisture of 15% or more within the first 5–7 hours. Soda lime with low initial moisture, which absorbs CO_2 only slighly and incompletely owing to rapid drying during the first time exposure to CO_2 containing gas, can well be reactivated by hydration, so that during the following exposure it exhibits its full neutralization activity. On the contrary, when the absorbent has adequate initial moisture, it maintains the absorption process until its full absorption capacity is exhausted during the first time use, and once exhausted soda lime can not be restored in its activity by re-humidification. These facts suggest the importance of precaution, during the storage and the use of soda lime, of keeping the optimum moisture, which is essential for the accomplishment of the CO_2 absorption processes such as carbonic acid formation, ionization, neutralization, and regeneration.⁴¹

The same significant influences of water on the CO₂ absorption efficiency were demonstrated experimentally with various intermittent and continuous gas flows using soda lime with different water contents packed in a canister, and it was realized that the initial moisture of soda lime between 15% and 19% on wet basis is at the optimum to accomplish the full absorption capacity with adequate absorption speed, specimens with lower moisture show more rapid exhaustion owing to rapid dehydration and those with higher moisture show slower absorption which permits more chance of CO₂ leakage from the canister.⁴²⁾⁴³⁾⁴⁴⁾ The problem of moisture and absorption activity of absorbents is not solved only in relation with the initial water content of absorbents but depends largely on the process of water migration in and out of the canister during the use. Complexity of this problem can be observed in an experiment where a three-chambered lucid canister is packed snugly with fresh soda lime with the optimum initial moisture and is intermittently ventilated upwards or downwards with 5% CO₂ containing gas. Changes in temperature, weight, moisture, and indicating color of soda lime in each chamber, as well as pH and the amount of water having left the canister, are observed until the absorption efficiency of the canister decreases to lower than 95%. The temperature elevation occurs almost in parallel with the shift of absorption zone, though somewhat in advance of the latter shift since heated gas is always directed and carries evaporated water downstream. This inevitable change of water distribution causes soda lime at the upstream layers in the canister

to get steadily dry, that in the middle to get slightly wetter for the first period and dry afterwards, and that at the downstream layers to get consistently wetter during several hours' use. Weight gains of soda lime consist of the absorbed CO_2 and the input-output balance of water, which are applicable to each of the chambers and also in the total canister. The migration of water with alkali from the absorbent granules is encountered more with the downward flow of gas. The differences between upward and downward flow directions are significant because the gravity affects the migration of water, and the upward flow appears advantageous for the maintenance of proper CO_2 absorption through the prevention of water maldistribution.^{42,43)} Such phenomenon is often observed clinically when a giant canister is used repeatedly without adequate precaution of changing its chamber position. Precaution should also include not to contaminate the patient's skin with alkalinelaiden water precipitate (pH of 13.9) which is highly caustic.⁴⁵⁾

7. Danger of channeling and bypassing

In the practice with an absorption system, keen attention should be paid to prevent channeling in the canister. Some canisters incorporate baffle rings to prevent so-called wall effect.²⁷⁾³²⁾⁴⁶⁾ Some others may preserve vestiges of a round baffle plate in the center which was originally designed for a to-and-fro absorber.⁴⁷⁾ Also, adequate design of spaces at the inlet and outlet ends are essential for an even gas flow distribution.³²⁾

The state of packed soda lime in a canister has much to do with the maintenance of absorption efficiency. For instance, packing of absorbent up to 85%, 70%, and 50% of a canister space decreases the duration of efficient absorption, approximately, to one half, one fifth, and one tenth, respectively, of that of a fully packed canister. If the upper surface of the absorbent has an incline, the channeling flow is further enhanced to the extent of leaking carbon dioxide at much earlier, or even at the initial stage of its use. Thus, canisters are originally designed to be filled snulgy and kept upright while in use, and uneven and/or inclined packing must strictly be avoided. The fact that a Waters canister, if packed loose to whatever minor extent, used in the horizontal position easily allows the flow to bypass over the thin upper absorbent layer but turning it to the vertical position restores the absorption efficiency demonstrates the importance of keeping the absorber upright.48) Another type of danger occurs when the CO₂ containing gas flow bypasses absorbent layers inside of the canister. It may take place at the contacting parts of the canister on-off valve or of the central down-tube in the canister when they are loose (Fig. 12). These internal leaks in the system affect the carbon dioxide absorption efficiency seriously but are hardly noticed.49>

8. Circuitry and efficiency of the circle absorption system

This section concerns the influence of relative location of the canister in connection with all the component parts of the semi-closed circle system.





- (A) Canister by-pass valve.
- Central down tube in the canister (e.g. (B) Heidbrink No. 18 or 19 absorber, Igarashi Jumbo Witsman absorber).

There have been few reports on the arrangements of CO₂ absorption circuits in relation to their efficiency. Previous authors attempted to classify the semiclosed or closed circle system according to whether the bag is placed on the expiratory or inspiratory side of the canister.⁵⁰⁾⁵¹⁾ This classification is rather from the view-point of system design and not a functional one. From the functional point of view, the system could primarily be divided by the breathing (or reservoir) bag (B) and the patient's lungs (pt.) into two sections; the expiratory side with an expiratory check valve (E) and the inspiratory side with an inspiratory check valve They are schematically illustrated with the left side arch and the right side **(I)**. arch, respectively, of the circle in Fig. 13. On these two sections, various locations could be allotted for a pop-off (or overflow) valve (P), a fresh gas inlet (F), and a canister (C). The basic arrangement of the circle system should, therefore, be in the order of $pt. \rightarrow E \rightarrow B \rightarrow I \rightarrow (pt.)$. It can be further divided by the two values into four segments; (Fig. 13)



Fig. 13. Four segments of the circle system.

pt.: patient E: expiratory valve

B: bag I: inspiratory valve

Outer circumference—gas movement during the expiratory phase, Inner circumference—gas movement during the inspiratory phase.

- S-1: from the bag to the inspiratory value (B-I),
- S-2: from the expiratory value to the bag (E B),
- S-3: from the inspiratory valve to the patient (I-pt.), and
- S-4: from the patient to the expiratory value (pt.-E).

The canister is symbolized as C_1 , C_2 , C_3 , and C_4 according to the segment it belongs to. For each one position of C, there are four functionally different positions of P, according to whether the pop-off value is located before or after the canister and in relation to the values as following;

for C_4 : (1) pt.-C, (2) C-E, (3) E-I, and (4) I-pt., for C_2 and C_1 : (1) pt.-E, (2) E-C, (3) C-I, and (4) I-pt., and for C_3 : (1) pt.-E, (2) E-I, (3) I-C, and (4) C-pt. (as illustrated by the circle in Fig. 14.)



Fig. 14. Four functionally different positions of P or F for one position of canister (e.g. C₃) (See text).
C: canister at one given position,
P: pop-off valve, F: fresh gas inlet.

The fresh gas inlet (F) can also assume four functionally different positions in the same manner in relation to the canister, the expiratory valve, and the inspiratory valve. Therefore, the lay-out of semi-closed circle system with a CO_2 absorber which is functionally distinguishable can be classified into the total of 64 (=4 for $C \times 4$ for $P \times 4$ for F), and each is simply exemplified by a circular diagram on which C, P, and F are arranged anti-clockwise or simply by placing the three symbol-characters from left to right, in their actual orders, as shown in Fig. 15. Capital

P or **F** indicates that it belongs to a different segment from **C** and accompanies a suffix number of the segment it belongs to. Small **p** or **f** represents that the pop-off valve or the fresh gas inlet is placed in the same segment that **C** belongs to and





Fig. 15. Symbolic nomenclatures and their diagrams of some representative semi-closed circle absorption circuits.

CR: controlled respiration, SR: spontaneous respiration.

Other abbreviations refer to Figs. 13 and 14.

Thickness of lines corresponds to the amount of flowing gas.

its position yields to the suffix number of C. In the former case, at least one check valve lies, except for C_3 and C_4 where two check valves may lie, between C and P or F. If P or F is located in S-1 or S-2 without insertion of C between E and I, it is described as P_{1-2} or F_{1-2} because its position on either side of B or at the intersection of the two segments cannot be strictly differentiated in the function.

Besides, there are other cases when E and I are placed in the Y-piece close to the patient as in a Swivel "Y" or a Sierra "Y" piece, and they must be differentiated on the diagram from the conventional anesthetic machines where E and I are attached to the canister *en bloc*, because the effect of the valves on checking the gas stream is enhanced as E and I draw near the patient. To denote the replacement of E and I by such "Y" valves, a symbol (Y) is added at the end of the three symbolcharacters. In such a case, "Y" often accompanies P, and, in case the pop-off valve is placed away from C in the same segment as in a Sierra "Y" piece, an arrow is added as $p \leftarrow$ in contrast to p which is close to C *en bloc*.

Using these symbols all possible arrangements of the semi-closed circle absorption system could be laid out. For example, the circuit diagram of Heidbrink No. 20 Absorber with I and E en bloc or Igarashi Witsman Jumbo Absorber is expressed as $\mathbf{pC_1f}$ (*Circle* 1 of Fig. 15), Dräger IIIa or IVa, Acoma TS-6 or PH-2, or Acome Infant Circle as $\mathbf{pC_1F_3}$ (*Circle* 2), BOC Boyle Mark 2, Dräger Ia, Igarashi V, or Igarashi Infant Circle 'Beta' as $\mathbf{C_2pf}$ (*Circle* 5), Heidbrink No. 9B as $\mathbf{P_4fC_2}$ (*Circle* 6), BOC Boyle Mark 3 or Ohio No. 60 Infant Circle as $\mathbf{C_2pF_3}$ (*Circle* 8), Heidbrink No. 18 or No. 19, or Acoma P-3A as $\mathbf{P_{1-2}C_3f}$ (*Circle* 9), and Mera Novus as $\mathbf{P_{1-2}fC_3}$ (*Circle* 11). The direction of gas flow through the canister could be indicated, if necessary, by an upward or downward arrow (\uparrow or \downarrow) immediately after C. The catalogue illustrations of Foregger Jumbo Circle Absorber CF-3 and of Morris Universal Absorber come under $\mathbf{C_2} \downarrow \mathbf{pF_3}$ (*Circle* 8), but by inter-

changing I and E, they can also be used more advantageously as $pC_1 \uparrow F_3$ (*Circle 2*) (Fig. 16).

The combination of the Heidbrink No. 20 Absorber and the Swivel "Y" piece is the example of the two valves (I and E) located near the patient, as expressed by $P_4C_1f(Y)$ (*Circle* 17 for spontaneous respiration or *Circle* 17' for controlled respiration). These two circles represent the circumstances where the pop-off valve located in between the shortened S-3 and S-4 is used for overflow and ejects a part of exhaled gas during the expiratory phase of spontaneous respiration or a part of inspiratory gas during the inspiratory phase of controlled respiration. The original Bloomquist Infant Circle Absorber used to be $p \leftarrow fC_1(Y)$ (*Circle* 12),⁵²) but when the bag holder with an inflow nipple is exchanged in position, it is modified into $p \leftarrow C_2 f$ (*Circle* 13) in which the gas squeezed out of the bag during the inspiratory phase of controlled respiration forms a back flow through C to be popped out through p. But in a recent model the bag holder and the fresh gas inlet are separated and it is represented by $p \leftarrow C_1 f(Y)$ (*Circle* 16) or $p \leftarrow fC_2(Y)$.

The following sections deal with the efficiency problem in the circuitry differences of the semi-closed circle CO_2 absorption system. The efficiency of the



Fig. 16. Two alternative arrangements of the Foregger Jumbo Circle Absorber CF-3 (See text).

circuit is dependent upon the efficacy in delivering the fresh state of gas into the patient's lungs and at the same time in eliminating the CO2 contaminated gas from the circuit. In other words, the efficient system is the circuit arrangement which permits the lowest possible CO2 concentration and the most faithful concentration to the fresh gas to be delivered into the lungs, during either spontaneous or controlled/assisted respiration. In terms of the economy of absorbent and fresh gas, the circuit is recommendable which wastes less oxygen and anesthetic gas before they reach the patient and concomitantly ejects more part of alveolar CO2 from the circuit content before it reaches the canister at a given inflow rate and ventilatory condition. The influence of relative location of the circuit components on the efficiency of semi-closed circle absorption system was evaluated by BROWN et al. in a model experiment in which the rate of utilization of absorbent was estimated from the 'apparent CO2 absorption capacity' of soda lime in the canister at a given condition of inflow and ventilation.⁵⁰⁾ EGER and ETHANS further reported an experimental study on the 'economy' of eight different arrangements of the semi-closed circle system under various inflow rates and ventilatory conditions with regards to the CO2 elimination rate through the overflow and the concentration ratio between the fresh and inspiratory gases.⁵¹⁾ FUKUCHI, one of our staff, observed the alteration of the flow pattern and of the CO2 concentration at various sites in the circuit while systematically changing its lay-out, and compared the load on the canister and its efficiency.53)

The relationship between the circuitry arrangement of semi-closed circle system and its efficiency can be estimated theoretically.⁵⁵⁾⁵⁶⁾ Providing, for simplicity, that the dead space effect, the turbulance effect in the circuit, the oxygen consumption and the anesthetic uptake of the patient are negligible, the following analytical procedures are possible:

Status-[A] 'The CO₂ exhaled by the patient is evenly mixed with the gas flowing into the expiratory circuit, a part of which is then spilled out of the circuit through P and the rest of which is later evenly mixed with the fresh gas from F to form the inspiratory gas. It is assumed that P performs no selective function as to its eliminating gas and there is no backward flow throughout the circuit.

[A-1] Provided C is in full efficiency, CO_2 concentrations in the expiratory and inspiratory gases are kept constant:

$$x=\frac{a}{v}, y=0$$

[A-2] When C is in null efficiency, CO_2 concentrations in the expiratory and inspiratory gas are expressed by exponential functions of time as:

$$x = \frac{a}{f} \{1 - \exp(-ft/V_A)\}, \quad y = a \left(\frac{1}{f} - \frac{1}{v}\right) \{1 - \exp(-ft/V_A)\}.$$

Fresh gas ratio in the inspiratory mixture also takes an exponential increase:

$$z=1-\exp\left(-\mathrm{f}t/\mathrm{V}_{\mathrm{A}}\right),$$

where $a = CO_2$ output of the patient (l/min.), v = flow at pt. to the expiratory circuit = tidal volume per minute (l/min.), $a \ll v,$ p = overflow rate though P (l/min.), $p \leq v,$ f = fresh inflow rate from F (l/min.), $p \leq f,$ t = time (min.), $x = CO_2 ratio in the expiratory gas,$ $y = CO_2 ratio in the inspiratory gas,$ z = ratio of fresh gas in the inspiratory gas,

 V_1 = circuit volume from F to P including pt. (l.),

 $V_2 =$ circuit volume from P to F including B (l.),

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 $V_2 = \text{cheat volume from T to T meruding D (i.),}$ $V = V_1 + V_2 = \text{mechanical volume of the circuit (l.),}$ $V_A = V_1 + \frac{v}{v-f}V_2 = V + \frac{f}{v-f}V_2 = \text{functional volume of the circuit in status-[A] (l.),}$ $V_A > V.$

Here $t \rightarrow \infty$, $x_{\infty} = \frac{a}{f}$, $y_{\infty} = a\left(\frac{1}{f} - \frac{1}{v}\right)$, and $z_{\infty} = 1$.

There is a transitional phase of the absorbent exhaustion from the fresh status-[A-1] to the terminal status-[A-2] during the practice, and it is during this phase that the clinical end point of absorbent life is encountered. However, y in [A-2] can be best utilized as an index of the CO₂ load on the canister. In status-[A], the suitable location for C is found in P—F where the flow rate in the circuit is minimal, viz. (v-p) l/min.

Status-[B] Another type of the circuit is that where the fresh gas from \mathbf{F} meets the expiratory gas to form an even admixture and a part of which is later spilled out of the circuit through \mathbf{P} . Efficiency of both CO_2 elimination and fresh gas conservation is lost remarkably by the combined effect of \mathbf{F} and \mathbf{P} . Gas components in the circuit are calculated as follows:

[B-1] Provided C is in full efficiency, CO₂ concentrations in the expiratory and inspiratory gases are:

$$x=\frac{\mathbf{a}}{\mathbf{v}}, \quad y=0.$$

[B-2] When C is in null efficiency, following calculations are made:

$$x = a\left(\frac{1}{f} + \frac{1}{v}\right)\{1 - \exp\left(-ft/V_{B}\right)\}, \quad y = \frac{a}{f}\{1 - \exp\left(-ft/V_{B}\right)\}, \text{ and}$$

$$x = 1 - \exp\left(-ft/V_{B}\right),$$
where $V_{B} = \frac{v+f}{v}V_{1} + V_{2} = V + \frac{f}{v}V_{1} = \frac{v+f}{v}V_{b} > V, \text{ and}$

$$V_{b} = V_{1} + \frac{v}{v+f}V_{2} = V - \frac{f}{v+f}V_{2} = \text{functional volume of the circuit in status-[B] (l.),}$$

$$V_{b} < V.$$

Here $t \to \infty$, $x_{\infty} \doteq a\left(\frac{1}{f} + \frac{1}{v}\right)$, $y_{\infty} = \frac{a}{f}$, and $z_{\infty} = 1$.

In status-[B], the suitable location for C is found in $P \rightarrow pt$. where the load on the canister is minimal. Integrated load of CO₂ on the canister is greater than in [A] so that the absorbent life in [B] becomes shorter. Comparison between [A] and [B] is grossly illustrated by Fig. 17. The common features between [A] and [B] are derived from the equations, as such 1) the larger the value of f, the slower the increase of CO₂ concentration and the faster the increase of fresh gas ratio, 2) the smaller the value of V, especially of V₂ in [A] and of V₁ in [B], and/or the larger value of v, the faster the increase of both the CO₂ and fresh gas ratios in the inspiratory circuit.



Fig. 17. Alteration of the CO₂ and the fresh gas ratios in the semi-closed circle absorption system (See text).

Beside [A] and [B] there are three more statuses of circuitry within all possible ranges of the circuit efficiency; one status with efficiency better than [A], one with efficiency between [A] and [B], and one with efficiency worse than [B]. The first one is the status where expired CO_2 is preferentially eliminated from the circuit, and occurs when features of ventilatory pattern suit well the characteristics (lumen, dynamic compliance, impedance *etc.*) of the circuit as well as the pop-off performance so that the fresh gas component may be retained efficiently within the system and the alveolar gas component may be proportionally well discarded.⁵⁴⁾ In the second one, the combined performance of F and P is an intermediate type between [A] and [B] so that the CO_2 ratio in the overflow falls in between x in [A] and y in [B]. The last one is the status where the fresh gas is selectively discharged out of the circuit, owing to the direct ejection of the main stream of inflow through P. Any possible efficiency of a given circuit with a given condition of inflow and ventilation falls into one of the above-mentioned five categories.

A model experiment in which the efficiency of various arrangements of the semi-closed circle absorption system was tested using fresh gas flow rate ranging from 2 to 9 l/min. under various ventilatory conditions revealed the following facts:⁵⁴⁾⁵⁷⁾⁵⁸⁾

(1) **P** is required to be located upstream to **C**, since the expiratory gas is partially expelled out of the circuit before reaching **C**. In this case, the load on **C** of CO_z , in the aspects of both quantity and flow characteristic of absorption, is decreased. (2) If **P** is located in S-1 or S-2, the circuit functions with the efficiency which does not vary greatly either under spontaneous or controlled respiration, though with somewhat less efficiency in the latter. Those circuits which have **P** in S-3 or S-4, *i.e.* without interposition of the expiratory valve between **pt**. and **P**, lose the efficiency completely under controlled/assisted respiration, since the gas ejected through **P** during the inspiratory phase contains almost pure fresh gas. With spontaneous respiration, however, **P** close to **pt**. in the expiratory circuit opens toward the end of expiration so that it may discard alveolar gas preferentially, and the efficiency improves.

(3) **F** is required to be located downstream to **C**. This, together with (1), contributes in increasing the efficiency of delivering fresh gas to **pt**. as well as in decreasing the flow rate through **C** allowing longer contact between the absorbent and the gas stream.

(4) If \mathbf{F} is located in S-3, the inflow during the expiratory phase steadily advances forward around the circle and only serves to dilute the expired gas. Such admixture of fresh gas is prevented by introducing \mathbf{F} between \mathbf{C} and \mathbf{I} .

(5) C is required to be located in the inspiratory circuit (S-1 or S-3). During controlled/assisted respiration the flow resistance caused by C on the patient's inspiration can be annuled. Between C_1 and C_3 , C_1 is rather preferred in the aspect of (4).

When C is located in S-2, with p upstream to C in the same segment according to (1) and (2), a retrograde flow is induced remarkably through C by controlled/ assisted respiration because the gas which once passes through C into B during the expiratory phase is pushed back through C during the succeeding inspiratory phase and expelled out through p. When C is located in S-4, there is no room for arranging an adequately efficient circuit, and such an arrangement as fC_4p (*Circle* 15 of Fig. 15) which is most inefficient belongs to this group.

(6) Comparison between the absorbers with I and E en bloc and those with I and E near pt. on the "Y" piece revealed that under controlled respiration the latter is somewhat superior in efficiency to the former, although both perform almost equally under spontaneous respiration. The function of I and E in checking the gas stream is generally enhanced as they draw near pt.

(7) The upward flow direction through C may be preferred to the downward (ref. Section 6).

All the above seven rules are not only consistent with the statements of BROWN *et al.*⁵⁰⁾ and EGER *et al.*,⁵¹⁾ but also supported by the following experimental results.

Those systems represented by $\mathbf{p} \leftarrow \mathbf{C}_1 \uparrow \mathbf{f}(\mathbf{Y})$, $\mathbf{p}\mathbf{C}_1 \uparrow \mathbf{f}(\mathbf{Y})$, and $\mathbf{p}\mathbf{C}_1 \uparrow \mathbf{f}$ are capable of performing the highest efficiency both under spontaneous and controlled/assisted respirations. After these follow $\mathbf{p}\mathbf{C}_2\mathbf{f}(\mathbf{Y})$, $\mathbf{p}\mathbf{C}_2\mathbf{f}$, $\mathbf{p}\mathbf{C}_1\mathbf{F}_3$, $\mathbf{p}\mathbf{C}_3\mathbf{f}$, $\mathbf{P}_{1-2}\mathbf{C}_3\mathbf{f}$, etc. These orders of the circuitry nominations correspond to those of their efficiencies in general, but in practice there are no discrete differences among them. $\mathbf{P}_4\mathbf{C}_1\mathbf{f}(\mathbf{Y})$, $\mathbf{P}_4\leftarrow\mathbf{C}_1\mathbf{f}$, $\mathbf{P}_4\leftarrow\mathbf{C}_1\mathbf{F}_3$, $\mathbf{P}_4\mathbf{C}_1\mathbf{f}$, $\mathbf{P}_4\mathbf{C}_1\mathbf{F}_3$, etc. are equally capable of the high efficiency performance only under spontaneous respiration, but the \mathbf{P}_4 -group loses the efficiency almost completely under controlled/assisted respiration.

In brief, from the standpoint of efficiency in gas exchange *per se*, the ultimate mode of the semi-closed system becomes identical to that of the non-rebreathing system, where the fresh gas rate equals the respiratory minute volume. Basic requirements for an ideal anesthetic system should include not only the economy of carbon dioxide absorbents and anesthetic gases, but also the ready and reliable control of the inspiratory gas constituents. The precautions against inadvertent or accidental hazards, mechanical stability and easy command should further be incorporated in the system. In view of the current trends in the selection of anesthetic agents, their administration, and ventilatory pattern, there should still be sought an anesthetic system versatilely competent for the highest functional efficiency.

9. Conclusion

The circle absorption system which has been most widely used in the present day practice depends for its elimination efficiency of expired carbon dioxide ultimately on the canister of absorbent placed in the circuit, while partially on the extent of gas exchange in the semi-closed system. The efficiency of the canister, therefore, becomes the primary critical factor in the assessment of the clinical

efficiency of the system for maintaining physiological inhalation anesthesia.

There have been a great deal of works carried out on the efficiency of absorbents, color indication, porosity, humidity, canister sizes and forms, air space, *etc.* All these should be integrated into a practical unity of knowledges for the proper elimination of carbon dioxide, realizing that absorbent efficiency has much to do with the patterns of respiration and the circuitry arrangements of the components of the system. Varieties of these factors must be kept in mind for intelligent and secure administration of inhalation anesthesia using a semi-closed or closed circle absorption system.

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of the monograph was delayed and finally suspended. As an editor of the monograph, I would like to make a humble apology to the author for a long delay in the publication of this important scientific work.

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