CARBON DIOXIDE ABSORPTION
THE CIRCLE VERSUS THE TO-AND-FRO

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ALTHOUGH the circle absorption circuit has become more popular than the to-and-fro, both systems possess advantages. This study of their comparable performances in absorbing carbon dioxide is relevant to eliminating extrinsic causes of respiratory acidosis during closed system inhalation anesthesia.

In 1943, Waters warned against errors in sampling for carbon dioxide composition in the assessment of the to-and-fro system (1). He emphasized that analysis of samples taken from the apparatus at a distance from the patient was worse than useless and gave a false sense of security. Waters advised, Only the atmosphere inhaled by the patient is important.

In 1943, Conroy and Seeviers pointed out that values of 0.1 per cent inhaled carbon dioxide reported by others were the result of sampling only at a certain point during inspiration (2). Inhaled carbon dioxide percentage of the order of 1.0 per cent was found early during use of both the circle and the to-and-fro.

Adriani and Rovenstine recommended that the airspace within an absorber equal the patient’s tidal volume (3).

The consensus since the introduction of the circle and to-and-fro systems has been that they provide a comparable efficiency of absorption. However, Waters recognized the inevitable increase in dead space in the to-and-fro and observed that the resulting increase in rebreathed carbon dioxide was occasionally not well tolerated (4).

As the quality of absorbents improves, it appears worthwhile to repeat the earlier comparisons of these two absorbing systems. The precision of the infrared analyzer makes such comparisons convenient and subject to repeated confirmatory trials. This report deals with the carbon dioxide absorbing efficiency of high-moisture soda lime in the same absorber used as a circle and as a to-and-fro circuit connected to a lung model.

METHODS

All studies were made with the Waters canister, 8 cm. by 13 cm. The circle system devised by Morris utilized the same canister. In some trials, valves were alternately inserted at the two commonly used sites, proximally in the Y-piece near the attachment to the airway.

Read before the annual meeting of the American Society of Anesthesiologists in Los Angeles, California, October 16, 1957, and accepted for publication December 11, 1957. The authors are in the Department of Anesthesiology, Roswell Park Memorial Institute, Buffalo, New York.

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or distally at the canister and bag. All valves used were of the small Acushnet type with rubber discs and central stems. The rigid gravity-lift valves which were available did not seat reliably when moisture accumulations caused "sticking" (5).

In all trials, the absorber was packed with 540 to 550 g. of high-moisture 4 to 8 mesh soda lime from the same well-sealed container.*

![Diagram of apparatus](image)

**Fig. 1.** Arrangement of apparatus. A reciprocating bellows simulating the lung is attached to either circle or to-and-fro system via the sample cell of the carbon dioxide analyzer. Enclosure of the bag with rigid drum permits continuous measurement of the simulated tidal volume.

A fixed-volume respirator served as a mechanical analogue of the patient's respiration. This unit permitted independent adjustment and control of the simulated patient's parameters, the following values of which were employed: tidal volume 500 cc., respiratory rate 16 per minute, respiratory dead space 120 cc., and carbon dioxide production of 300 to 320 cc. per minute. A thermostatic regulator on a carbon dioxide tank delivered the gas through a flowmeter, a wet-test meter, and a multiperforated catheter coiled inside the moving bellows of the fixed-volume respirator. The carbon dioxide flow rate into this simulated lung was adjusted to give an alveolar carbon dioxide concentration of 5.7 per cent initially. With failure of complete carbon dioxide removal, progressive elevation of this concentration occurred.

The ventilation analogue was coupled to one end of the standard sampling cell of the Liston-Becker analyzer and the circle or to-and-fro system was connected to the other end. The breathing bag of the system under test was enclosed within a 55 gallon drum for recording volume. A Statham strain gauge measured the resulting pressure change in the drum (fig. 1). This signal was calibrated in terms of volume change of the breathing bag by adding 100 cc. increments of air from a syringe. A Sanborn direct-writing oscillograph recorded

* Indicating Soda Lime, Mallinkrodt Chemical Works.
simultaneously the respired carbon dioxide concentration and the tidal volume (fig. 2).

The procedure, previously described for measurement of physiologic dead space (6), was adapted for the determination of the external dead space in the to-and-fro system (fig. 2). In the present application, the carbon dioxide and volume records, run at 50 mm. per second, are analyzed from the beginning of inspiration to determine the quantity of carbon dioxide rebreathed as a result of the progressive depletion of active soda lime at the proximal (patient's) end of the to-and-fro canister.

![Graphs showing carbon dioxide concentration and volume over time.](image)

**Fig. 2.** Representative records. Early and late determinations of external dead space and inspired carbon dioxide concentration demonstrate the performances after 3¾ hours of the 550 g. circle and the 550 g. to-and-fro absorbers.

In a continuous record of respired carbon dioxide, the ascending or descending limbs of the curve may be reconstructed to represent a square wave change in concentration. As a convenient approximation, a perpendicular line may be placed so that the paired triangles subtended are equal in area (fig. 2). The intercept produced by extension of this perpendicular on the simultaneous volume record may be used to determine either the expiratory or the inspiratory dead space. Corrections for the slight error in the equal areas method due to an allinearity of the carbon dioxide analyzer were not made. This error is negligible and essentially systematic.

For the circle system, these analyses of dead space were also made. Performance of each system in absorbing carbon dioxide was also evaluated by the progressive elevation in average inspired carbon dioxide concentration and the accumulating dead space resulting therefrom.
Results

The to-and-fro system yielded an average inspired carbon dioxide concentration of 0.64 per cent initially (fig. 3). This value reflects an absolute minimum of rebreathing with the to-and-fro which is the result of the space in the proximal end of the canister. This value, representing initial performance of the to-and-fro absorber coupled to a patient’s tracheal tube, would be about one per cent higher when an oronasal mask is used. The progressive elevation in average inspired carbon dioxide was essentially linear for two and one-half hours at which time it exceeded 2 per cent. Terminal failure of absorption followed another linear but steeper function (fig. 3). After three and one-half hours, the average inspired concentration reached over 3 per cent. The simulated carbon dioxide input rate for this trial was 320 cc. per minute.

![Graph showing comparison of carbon dioxide absorption performances of to-and-fro absorption systems. The to-and-fro system yielded an initial inspired carbon dioxide concentration of 0.64 per cent as compared with 0.3 per cent for the circle system. With continuous performance, the to-and-fro system failed progressively, providing an average inspired carbon dioxide concentration of 1.0 to 3.0 per cent higher than that with the circle system.](image)

Under comparable conditions, except for an input rate of 300 cc. carbon dioxide per minute, the same absorber used in a Morris circle yielded an average inspired carbon dioxide concentration of 0.3 per cent initially, 0.75 per cent after two and one-half hours, and less than 1.0 per cent after three and one-half hours.

Figure 4 depicts the above data plotted against the volume of carbon dioxide absorbed per unit weight of absorbent. This method of plotting allows comparison of absorbers of different size, subject to different loads of carbon dioxide.

The progressive increase in that fraction of expired carbon dioxide
which is rebreathed is represented in terms of absolute dead space in figure 5. The initial dead space was 50 cc. for the to-and-fro, but the volume rebreathed increased almost linearly to reach 150 cc. by the

![Graph 1](http://anesthesiology.pubs.asahq.org/pdfaccess.ashx?url=/data/journals/jasa/931669/)

**Fig. 4.** Relationship between average inspired carbon dioxide concentration and absorption performance for circle and to-and-fro systems employing identical lime compartments. This plot permits comparison of efficiency of absorbers of different size and of performances which vary in test conditions, that is, carbon dioxide production of patient.

![Graph 2](http://anesthesiology.pubs.asahq.org/pdfaccess.ashx?url=/data/journals/jasa/931669/)

**Fig. 5.** Effects of absorvent depletion upon the patient’s effective dead space. Dead spaces are comparable at the start for both systems having fresh lime. Depletion of proximal lime in the to-and-fro system produces progressive accumulation of dead space. In contrast, the performance of the circle system does not affect effective dead space during its useful life.
time the absorber had removed 55 liters of carbon dioxide. There-after, the dead space increased at about twice the previous rate.

The comparable plot of performance of the circle shows a constant dead space of 45 cc. throughout the entire period of absorption. This

![Graph showing end-inspired CO2 % vs. hours for To & Fro and Circle systems.]

**Fig. 6.** Example of improper sampling in comparison of absorption systems. The end-inspired carbon dioxide concentrations were obtained during the performances of figure 3. The relatively lower values shown here at any given time are the result of the terminal washout fraction of inspired gas and fail to account for the rebreathed carbon dioxide in the initial inspired fraction.

![Graph showing end-inspired CO2 % vs. CO2 absorbed (L/100 Gm).]

**Fig. 7.** Erroneous comparison of to-and-fro and circle systems. These data were obtained by sampling the carbon dioxide concentration in the terminal fraction of inspired air. The apparent similarity in efficiencies of these systems ignores the total carbon dioxide re-breathed. Similarly, erroneous conclusions may result from analyses of samples taken from the breathing bag.
rebreathing is primarily the result of the washout of the conventional Y-piece attachment. Changing the valve positions from the distal to the proximal ends of the breathing tubes lowered the dead space only to 30 cc. When the conventional Y-piece was replaced by a valved Y attachment, the dead space was only 10 cc.

To determine the effects of other sampling methods, these performances of the circle and to-and-fro were analyzed and replotted with end-inspiratory carbon dioxide concentrations instead of average inspired concentrations (figs. 6 and 7). These results show absorption performances comparable to those reported in earlier studies when only static methods were available (2, 3).

Channeling at the walls was apparent in both systems. The horizontally positioned to-and-fro canister required more careful packing and handling to prevent excessive channeling on the upper side than did the vertical canister of the circle system. Table 1 indicates typical performances.

| TABLE 1 |
| COMPARISON OF PERFORMANCE OF TO-AND-FRO AND CIRCLE CARBON DIOXIDE ABSORBERS |

<table>
<thead>
<tr>
<th>Canister</th>
<th>Lime Compartment (cc.)</th>
<th>Lime Capacity (ml)</th>
<th>Initial Effective Air Space</th>
<th>Performance in Hours to 0.5 Per Cent Increase in Inspired CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 cm. X 13 cm. to-and-fro</td>
<td>630</td>
<td>550</td>
<td>370</td>
<td>1</td>
</tr>
<tr>
<td>8 cm. X 13 cm. circle</td>
<td>630</td>
<td>550</td>
<td>-370</td>
<td>2½</td>
</tr>
</tbody>
</table>

Since common clinical practice involves intermittent use of absorbers, particularly of the to-and-fro system, the performance studies were repeated for both systems with half-hour rest periods at half-hour intervals. Detailed results of these studies are not presented because they did not differ significantly from continuous performances. The cyclic use of the absorbers produced no sustained improvement in carbon dioxide absorption. The average inspired carbon dioxide concentration decreased only slightly following the rest period and within five minutes had actually increased to a value somewhat above that just prior to the rest period. No evidence favoring regeneration as a practice for prolonging absorptive activity was elicited. The slight apparent improvement in performance was too evanescent to be of any clinical value. Similarly, the gradual increase in effective dead space during intermittent use of the to-and-fro paralleled remarkably the results reported here for continuous performance.

**Discussion**

The inevitable increase in equivalent dead space of the to-and-fro system is not a new observation. Quantitative estimates of its magnitude contribute no more than an approximation of the effect in any

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given patient. However, these results call attention to the accelerated terminal failure of the absorber to eliminate expired carbon dioxide and demonstrate the need for an ever-increasing tidal volume to compensate for the increasing dead space.

Another significant observation relates to the importance of total sampling of all respired gas in assessing carbon dioxide absorption. Previous comparisons of the circle and to-and-fro did not have the technical advantages of rapid simultaneous analyses of carbon dioxide and volume. To avoid including dead space air in the sample tested, only end-inspiratory gas was sampled. Since this gas penetrates deepest into the to-and-fro canister, its carbon dioxide concentration should also be lowest. It would be longer in contact with absorbent and have the best chance to reach active absorbent. Thus, results showing the equivalence in performance of the to-and-fro and circle or the superiority of the to-and-fro would be obtained as depicted in figures 6 and 7 when end-inspiratory gas is sampled. However, this sample is not representative of all the air inspired.

Simultaneous recording of carbon dioxide concentration and volume permits measurement of both the average inspired carbon dioxide concentration and the equivalent dead space. The latter volume represents that fraction of the expired air which is rebreathed upon the next inspiration without carbon dioxide removal. The average carbon dioxide concentration during three and one-half hours increased from 0.6 to 4.5 per cent with the to-and-fro and from 0.3 to 1.0 per cent with the Morris circle. These performances involved a progressive increase in dead space up to 200 cc. for the to-and-fro and a constant value of 45 cc. for the circle. Thus, application of the rapid simultaneous techniques leaves little doubt as to the superiority of the circle in terms of carbon dioxide absorbing efficiency.

The exhaustion patterns differed significantly in the circle and to-and-fro systems employing the same absorber. Silhouettes depicting these patterns, both of which reveal channeling, are shown in figure 1. Examination of the discoloration of the Indicating Soda Lime immediately at the termination of each performance study showed consistently a preferred central flow path in the horizontally placed absorber of the to-and-fro system, and, conversely, a preferred peripheral flow path in the vertically placed circle system. Before using the absorber in the horizontal position, considerable care had to be taken to obtain tight packing of lime to avoid the shunt path over the upper portion of the absorbent which results from settling of granules. Trials of the to-and-fro in the vertical position were not but should be made. Position of the absorber, however, will not prevent the inevitable depletion of activity of the proximal lime in the to-and-fro system.

The failure of regenerative cycling to influence absorptive performance confirms earlier studies (7). While rest periods may be advantageous to allow cooling of the to-and-fro absorber, the depletion of the lime is determined by the total liters of carbon dioxide it has
absorbed. Advantages of the to-and-fro which relate to ease of sterilization, lesser compression volume of the breathing circuit during controlled ventilation, and convenience at the head of the table are well recognized. The prevention of carbon dioxide accumulation, however, calls for either a fresh absorber after 45 minutes use or a progressive increase in the adult patient’s tidal volumes by 50–75 cc. every hour. This implies for each hour of use an increase in ventilation of 0.75 to 1.5 liters per minute. Even this compensation becomes entirely inadequate after ninety minutes as an accelerated terminal failure occurs. It must be emphasized that the patient with an increased carbon dioxide production will place a proportionately greater load on the to-and-fro absorber. In any event, his response to carbon dioxide may be anticipated at the start of use of the to-and-fro if a mask is employed.

**Summary**

Comparisons of the to-and-fro and circle systems of carbon dioxide absorbers were made with identical lime compartments, the 8 cm. by 13 cm. standard Waters canister. Pertinent parameters of the patient were simulated as to tidal volume, rate, and carbon dioxide output and were maintained the same for evaluation of the two absorbing systems.

A progressive increase in external dead space was found with the to-and-fro absorber. Average inspired concentration increased linearly until terminal failure. For the circle, little or no change in external dead space or average inspired concentration occurred until terminal failure.

This increase in external dead space requires the patient to progressively increase tidal volume. The to-and-fro absorber has a very limited life if this compensatory increase in tidal volume is not possible. A half-hour cycle of resting absorbers did not extend the useful life. An hour to one and a half hours is recommended as a limit for safe use of lime in the closed to-and-fro system in adults.

This study was supported by funds provided under Contract DA-49-007-MO-507 with the Division of Research and Development, Office of the Surgeon General, Department of the Army

**REFERENCES**