CARBON DIOXIDE ACCUMULATION VALVE LEAKS AND INADEQUATE ABSORPTION[1,2]

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In the types of breathing circuits commonly used in general anaesthesia, valves are utilized to provide either unidirectional gas flow or a pressure release (pop-off) In the closed circle, satisfactory function is dependent upon the integrity of the valves, the occurrence of a defect allows reflux and an opportunity for rebreathing In practice, two types of valve are in use to provide the unidirectional flow in the closed circle, the gravity-returned rigid disc and the rubber or plastic mushroom The former type has been observed to become fixed in the open position during use, although more common at the expiratory valve, where condensation of water vapour from the patient's exhaled gases occurs, sticking has also been noted at the inspiratory side The mushroom type of valve may become "fluted," wherein one segment of the valve protrudes through the supporting grid and is retained thereby, such an occurrence is usually the result of exposure to elevated back pressures as occurs when one forcibly breathes against a single valve

It is primarily with the effect of leaks in these valves, expressed in terms of carbon dioxide rebreathed, that this presentation is concerned However, as adequate carbon dioxide absorption is also of prime importance in the closed circle system, some observations are offered on the use of canisters, both in this and the to-and-fro system

PROCEDURE AND EQUIPMENT

The procedure was designed to demonstrate the effect of valve leak or insufficient carbon dioxide absorption, at the same time taking into account the physiological response obtained from an unmedicated patient

An Ohio 19-type circle and absorber was utilized for observations on its own built-in valves and other substituted valves in differing arrangements, with and without deliberately introduced leaks which simulated those which were observed in clinical practice For the to-and-fro system, a standard Waters (8 x 13 cm) canister was used

The valves investigated were those built into the Ohio 19 canister and both the yoke and individually mounted valves produced by Anesthesia Associates, Inc

Two Ohio 19 canisters were used, one contained fresh lime, the other had been used until it was allowing passage of 2 per cent carbon dioxide Similarly, the Waters canisters contained fresh and used lime

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The analysing equipment consisted of a Liston Becker (Model 16) carbon dioxide analyser and a pneumotachograph. The dead space of this analysing equipment and mouthpiece was roughly that of a conventional mask, 110 cc. These two instruments, suitably calibrated, enabled us to obtain continuous measurement of flow rates and carbon dioxide concentrations of the respired gases. The signals from the carbon dioxide analyser and from the differential strain gauge attached to the pneumotachograph were amplified and recorded on Sanborn equipment. These two records, carbon dioxide concentration and flow, yield several parameters, including dead space.

Figure 1 illustrates the arrangement of mouthpiece, analysing equipment, and anaesthetic apparatus.

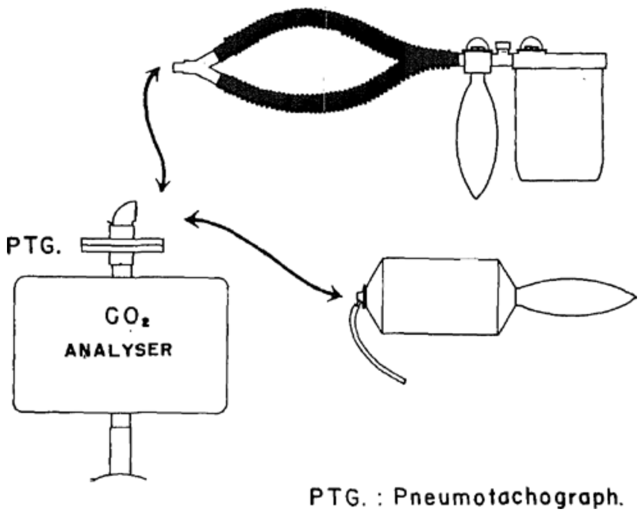

FIGURE 1. Illustrating the arrangement of mouthpiece, analysing equipment, and anaesthetic apparatus. The arrows indicate the position of attachment of the parts during the procedures.

The subject, unmedicated but under basal conditions, was first required to breathe through the analysing equipment until a steady state had been achieved. Thereafter, the various arrangements of anaesthetic apparatus were attached for short periods of time and their immediate effects recorded. Between procedures, a short period of air breathing was allowed during which the apparatus was thoroughly flushed and filled with carbon dioxide-free air. During observations on the closed circle and to-and-fro system, oxygen was added throughout at a rate of 250 cc. per minute. The subject had no knowledge of the particular changes that were being utilized and had been trained by previous experiments to allow his natural respiratory responses to occur without inhibition.

Results

The results given in Table I are obtained from single breaths at the time stated after the beginning of each procedure. These figures refer solely to the total volumes of gas and carbon dioxide content entering and leaving the anaesthetic apparatus, effects of instrumental dead space are excluded. Inspired carbon dioxide concentrations up to 6.3 per cent are recorded with a corresponding increase in tidal volume of almost 350 per cent. The conditions of the experiments would not allow the development of a steady state and in certain cases the changes were progressing rapidly towards carbon dioxide concentrations which would have caused considerable distress to our subject and denied the possibility of continuing with other observations. We noted also that some of the responses appeared anomalous. Four of our observations include alveolar carbon dioxide concentrations below the value obtained when the patient was breathing ambient air only through the analysing equipment. It will be noted that where such lowered alveolar carbon dioxide concentrations occurred, the patient's tidal volume is somewhat elevated. On examining the time interval from the previous procedure, we noted that we had allowed insufficient time for sustained response to have subsided.

TABLE I

Fresh Lime

Procedure	Circuit	Valves	Alveolar CO_2 (%)	Tidal volume (cc)	Rate (breaths per min)	Time (min)	Equivalent added dead space (cc)	Average inspired CO_2 (%)	Total CO_2 inspired (cc)	Minimum inspired CO_2 (%)
2	Closed circle	19 Exp valve leak	6.1	725	10.5	1.25	170	1.4	10.5	3.1
3	Closed circle	19 Ins valve leak	6.0	895	12.0	1.5	280	1.9	17.5	0.3
4	Closed circle	19 Both leak	6.7	955	9.5	1.5	830	5.9	56.0	3.8
5	Closed circle	AA Intact	5.3	825	7.0	1.75	10	<0.1	0.5	0.0
6	Closed circle	AA Ins valve leak	6.1	735	8.5	1.25	185	1.5	11.0	0.0
18	Closed circle	SS At canister	4.4	1200	7.5	1.75	45	0.2	2.0	0.0
19	Closed circle	SS At patient	4.9	640	8.0	0.5	10	0.3	2.0	0.0
20	To and fro closed		5.6	790	7.5	1.0	40	0.3	2.2	0.0
Air			5.8	510	9.0	3.25	0	0	0	0.0

Valves 19—gravity returned fibre disc type mounted on Ohio 19 canister
AA—Anesthesia Associates valves mounted in yoke
SS—Anesthesia Associates individually mounted valves (Sierra Silicone)

From the figures obtained, it is apparent that in closed circle, or to-and-fro systems, which are functioning correctly, there is only a slight elevation of inspired carbon dioxide. The introduction of the valvular leak in the circle system produces an immediate rise in the inspired carbon dioxide level. The additive effect of a double valve leak is demonstrated. The rapidity with which such levels can be attained can be seen from the reproductions of specimen recordings in Figure 2.

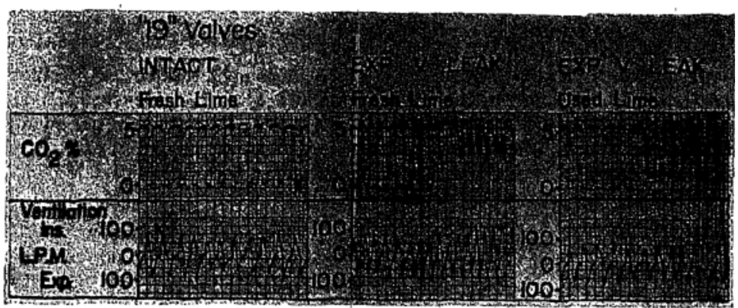

FIGURE 2. The rapid rise in the inspired carbon dioxide level immediately following the attachment of the anaesthetic apparatus is demonstrated.

DISCUSSION

The significance of these grossly elevated values for inspired carbon dioxide levels is most dramatically expressed in terms of ventilation required to maintain carbon dioxide homeostasis. The figures given in the table for tidal volume are expressions of the subject's efforts to achieve this goal under the various circumstances. In the absence of the steady state, they do not depict the actual increment

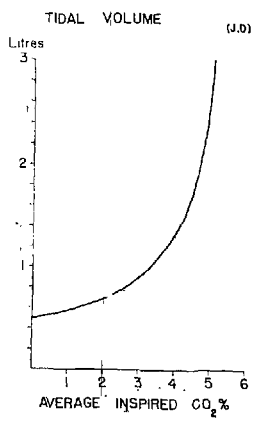

FIGURE 3

in ventilation necessary to compensate for a particular inspired carbon dioxide level. These relationships are expressed in the basic equation for pulmonary ventilation for a single breath at fixed frequency (1):

$$\text{tidal volume} - \text{dead space} = \text{alveolar ventilation} = \frac{CO_2 \text{ production}}{\text{alveolar } CO_2 \text{ fraction} - \text{inspired } CO_2 \text{ fraction}}$$

The graph (Figure 3) calculated from observations upon this particular subject (carbon dioxide production 192 cc. per minute) while breathing ambient air illustrates the alterations in his tidal volume at a rate of nine breaths per minute which would be required to achieve homeostasis with various levels of inspired carbon dioxide. To combat some of the levels of inspired carbon dioxide which were found in our procedures (Tables I and II), it can be seen that the ventilation

TABLE II

USED LIME

Procedure	Circuit	Valves	Alveolar CO_2 (%)	Tidal volume (cc)	Rate (breaths per min)	Time (min)	Equivalent added dead space (cc)	Average inspired CO_2 (%)	Total CO_2 inspired (cc)	Minimum inspired CO_2 (%)
1	Closed circle	19 Intact	6.7	1280	6.5	3.5	335	1.8	22.5	1.5
2	Closed circle	19 Exp valve leak	7.5	1310	7.5	3.5	855	4.9	64.5	4.4
3	Closed circle	19 Ins valve leak	6.4	1235	7.5	7.5	685	3.6	44.5	1.2
4	Closed circle	19 Both leak	7.1	1730	8.0	5.5	1525	6.3	109.0	4.7
5	Closed circle	AA Intact	6.1	680	8.5	4.75	155	1.4	9.5	1.0
6	Closed circle	AA Ins valve leak	6.1	915	7.0	4.25	390	2.6	24.0	0.5
7	Closed circle	AA Exp valve leak	6.0	930	7.5	3.75	395	2.5	23.5	2.0
18	Closed circle	SS At Canister	5.3	1225	5.0	3.25	315	1.4	17.5	1.0
19	Closed circle	SS At patient	5.8	740	8.0	3.0	160	1.3	9.5	1.0
20	To-and-fro closed		5.8	705	10.0	5.25	120	1.0	7.0	0.5

VALVES 19—gravity returned fibre disc type mounted on Ohio 19 canister
AA—Anesthesia Associates' valves mounted in yoke
SS—Anesthesia Associates' individually mounted valves (Sierra Silicone)

of a very high order is required to prevent carbon dioxide accumulation. As the inspired level of carbon dioxide approaches that of the subject's resting alveolar value, the required ventilation approaches infinity, with even higher values, no amount of effort would obtain homeostasis.

It will be noted that our subject did not manage to maintain his alveolar carbon dioxide at his resting level of 5.8 per cent during many of the procedures (2).

The results of including in the circuit a canister containing expended lime were as expected. The canister used for these observations, as already stated, had been correctly packed and utilized until it was allowing passage of 2 per cent carbon dioxide. At this point, the indicator in the granules on the surface had just begun to change colour which a casual glance would probably not have detected. We know from previous experiments that there is a considerable period between the onset of incomplete carbon dioxide absorption and the appearance of indicator change in the surface granules in this particular canister. Thus, to rely upon inspection of the surface lime is fallacious. Furthermore, there is no means of observing the lime indicator during use.

In the results obtained during the procedures when the Anesthesia Associates' valves were used instead of the valves on the canister, there are marked differences in the equivalent added dead spaces with the different valve positions. An equivalent added dead space of 10 cc. results with the yoke valves and fresh lime in the canister; it is increased to 40-45 cc. when the individually mounted valves are placed at either the patient or canister end of the corrugated tubes of the circle (Procedures 5, 18, 19). The values obtained for equivalent added dead space with used lime in the canister in the same procedures confirm the effects of the different placement of the valves.

Under normal clinical conditions for general anaesthesia, it is not always feasible to obtain continuous monitoring of respired carbon dioxide. Moreover, as drugs (3, 4) and surgical procedures modify the physical signs of carbon dioxide retention, its diagnosis becomes complicated and unreliable. This, in turn, signifies that the detection of elevated levels of inspired carbon dioxide is difficult. If the effect of the drugs and procedures of surgery upon the items in the equation for pulmonary ventilation are considered, the maintenance of carbon dioxide homeostasis is seen to be subject to many variables. Thus, increases in inspired carbon dioxide must be compensated by increases in ventilation commensurate with alterations in the other items concerned. It may be that the conditions of anaesthesia are such that a patient is capable of spontaneously maintaining a steady alveolar carbon dioxide concentration; more often this is not so, and it rests with the anaesthetist to augment the ventilation.

These studies demonstrate the fallacy of depending on even the most modern equipment and valves to provide reliable carbon dioxide elimination. That such levels of inspired carbon dioxide can occur, and be respired by subjects whose responses are obtunded, provides cause for some consideration.

It would seem opportune, at this point, to observe that where valvular defects occur and provide opportunity for rebreathing, the oxygen concentration will fall as the inspired carbon dioxide rises (5).

Comments

Although these observations have been performed with particular makes of equipment and valves, similar faults have been noted in other manufactured apparatus. The indictment of valves and soda lime containers is intended for all designs which respectively are subject to develop leaks or provide no simple means of determining adequate carbon dioxide absorption.

Summary

The effects on an unmedicated subject of valvular leaks and inadequate carbon dioxide absorption in a circle and a to-and-fro system are investigated. The results are expressed in terms of elevated percentages of inspired carbon dioxide, and the increase in ventilation required to maintain carbon dioxide homeostasis in a particular subject is calculated.

Attention is drawn to the dangers of high inspired carbon dioxide levels in general anaesthesia and the necessity for maintaining adequate ventilation.

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RÉSUMÉ

Dans les circuits qu'on emploie courament en anesthésie générale, on place des valves, soit pour donner à l'atmosphère une seule direction, soit pour limiter sa pression. Dans le cas du circuit fermé, pour qu'il fonctionne de façon convenable, il faut que les valves soient étanches. Toute défectuosité entraîne un reflux et permet la respiration de l'air exhalé. Le premier but de ce travail est de montrer les conséquences des défectuosités de ces valves en ne considérant que la quantité de gaz carbonique réinspiré.

D'après les chiffres obtenus au cours de cette étude, il est manifeste que si les systèmes fonctionnent bien, qu'il s'agisse du circuit fermé ou du "va et vient," le taux d'élévation du gaz carbonique n'est que très faible Si l'on provoque une défectuosité à une valve du circuit, le taux de gaz carbonique réinspiré s'élève immédiatement. Si la défectuosité est provoquée aux deux valves, les conséquences s'additionnent. La rapidité avec laquelle de hautes teneurs en gaz carbonique peuvent être atteintes est considérable ainsi qu'on peut le constater par les graphiques de la figure 2

Dans l'occurrence de taux de gaz carbonique aussi élevés dans le circuit, le volume de ventilation nécessaire pour éviter l'augmentation du taux de gaz carbonique dans le sang devient effarant Si l'on intercale dans le circuit un contenant de chaux efficace, les résultats sont éloquents comme le montrent les tableaux Ces études démontrent l'imprudence sinon l'erreur de compter sur la machine, même la plus moderne, pour assurer l'élimination du gaz carbonique Quand il survient des défectuosités aux valves, il s'ensuit une élévation du taux de gaz carbonique à cause de la réinspiration, et, si le taux de gaz carbonique augmente, le taux d'oxygène va diminuer

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