CARBON DIOXIDE CONCENTRATIONS FOUND IN VARIOUS ANAESTHETIC CIRCUITS

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Some investigations have been carried out over a period of time on the carbon dioxide concentrations returned to the patient in various types of partial and total rebreathing anaesthetic apparatus.

A number of workers have published data of this type, based, however, on gas analysis of discrete samples, obtained either by turning a tap in time to the patient's respirations, or by collecting complete inhalations, as used by Conroy and Seevers (1943) and Woolmer and Lind (1954). We have found that the first method of "snatch-sampling" with a tap gives uncertain and often incorrect results, and have discarded it. This same fault also occurs in Woolmer's method, since the sampling is again dependent on turning a tap in phase with the respirations. In the method of Conroy and Seevers, a breathing machine was used in which the inhaled gas was retained in a reservoir bag which was part of the machine. These workers obtained very high concentrations, due largely to mixing of inhaled and exhaled gases which was not allowed for.

METHOD

It seemed to us that the simplest solution of this problem was to devise a system of continuous analysis of the gases at the face mask. The time lag of such a system would have to be sufficiently short to enable all variations in concentration over the breathing cycle to be observed and measured.

A laboratory-constructed infra-red gas analyser described by Fowler (1949) has been successfully used by Dubois et al. (1952) in an investigation of the variation of carbon dioxide concentration at the lips during respiration under various conditions. More recently, Dornhorst et al. (1953) have adapted an infra-red gas analyser to follow this respiratory variation, using it as a clinical test for emphysema.

An infra-red gas analyser was available, and, in view of the success of these workers, was modified for our purposes. This was done by cutting out the meter circuit, including the rectifier and smoothing condenser, so that a modulated A.C. signal, of amplitude dependent on the carbon dioxide concentration in the analysis cell, was obtained. This signal was then fed to a cathode-ray oscilloscope, where the amplitude could be measured at any part of the respiratory cycle by applying a variable known voltage to zero the required portion of the trace on the graticule.

In use, there is always a slight drift on
the zero and the sensitivity, so these must be checked occasionally, using respectively dry carbon dioxide free air, and a standard carbon dioxide/air mixture.

When the gases in a breathing circuit are analysed, the sample will normally be saturated with water vapour at a slightly elevated temperature. Apart from any risk of condensation, large quantities of water vapour will interfere with the analysis, since the vapour has an absorption band in the infra-red, close to that of carbon dioxide. Chemical drying of the gas is inadmissible, as the volume of the sample lead must be kept as small as possible, and the flow kept reasonably smooth. Hence the water vapour was largely removed by passing the sample through a small cold trap immersed in a solid carbon dioxide/trichlorethylene freezing mixture. It was found that the optimum temperature for this was between -10°C and -20°C; a lower temperature cooling the analysis cell and giving a high result.

When the apparatus is used in a closed breathing circuit, the sample must obviously be returned to the system. The point where this is done must not be close to the sampling point, or interference may occur, as the two streams will probably be out of phase with respect to the respiratory variation. It has been found satisfactory to return the sample to the breathing machine where one is used (see later) or to an endotracheal catheter in a human patient. In certain systems, it is permissible to return the sample to the rebreathing bag. Since this means that gas is transported from one part of the system to another, interference will occur unless either the flowrate through the analyser is kept very low, or sampling is only done for short periods. In our work, the second course was adopted, since a flowrate of about 1.5 litres per minute was needed to avoid mixing of the gases before they reached the analysis cell, though this minimum flow depends to some extent on the conditions. In any event, it is essential that the connection to the sampling point has as small a volume as possible, but without undue constriction, or the pressure in the analysis cell will be reduced, giving a low result. It has been found that a number of respiations may be observed in a single sampling operation without appreciably disturbing the system.

Hence, the apparatus was as shown diagrammatically in figure 1; in this, for the sake of clarity, the circulatory system for the unused absorption tubes and the analyser case is omitted.

If it was desired to carry out analyses in the presence of another gas which absorbed infra-red radiation in the same wave-length range as carbon dioxide, such as nitrous oxide, this interference was suppressed by filling the unused large analysis cells on both sides of the analyser with this gas.

If desired, the oscilloscope may be combined with a camera, but this was not found necessary in the present work.

For most of the work described here, a mechanical breathing machine was used instead of a human patient. The breathing machine used was similar in principle to that of Adriani (1941), and is illustrated in figure 2. In essence, a bell was moved up and down in a heated tank by a pulley-and-string system connected to a motor, so that the rate and tidal volume
could be adjusted. A tube roughly equal in volume (150 ml) to the average physiological deadspace led to the inside of this bell, and a second tube was used to introduce carbon dioxide at a controlled flow-rate. In our tests, the deadspace was increased externally by a further 150 ml to represent the use of a face mask. The liquid in the tank (a solution containing sodium benzoate and sodium nitrite, to inhibit corrosion) was maintained at 37°C.

This technique has been successfully used in a number of systems. With a human subject, a satisfactory variation in carbon dioxide concentration at the face mask was obtained, which was practically identical with that reported by Fowler (1949), Dubois et al. (1952) and Dornhorst et al. (1953) for normal respiration. Use of the breathing machine gave rise to some rounding of the trace, due to the much closer approximation of the motion to a sinusoidal form, but the fundamental character was similar, and the resemblance was considered sufficiently close for our purposes.

A further point should be made here...
regarding the breathing machine tests. In our machine, the whole of the carbon dioxide inhaled is returned, together with that led in, giving a rising exhalatory concentration. With low concentrations in the inhaled gases, this effect is insignificant, but with higher concentrations will have the effect of increasing somewhat the "alveolar" concentration. When a patient is used, this increase does not occur, but some increase of exhalatory concentration does still occur, due to the recycling of that carbon dioxide present in the deadspace at the end of inhalation. To obviate this would have involved considerable constructional and operational difficulties, and this was not carried out, particularly in view of results with human subjects.

It is considered that the analyses, in the range 0-4 per cent carbon dioxide, are correct to ±0.05 per cent carbon dioxide.

RESULTS

Circle Type Absorbers.

The principle on which this type of unit operates on closed circuit is such that it is normally impossible for gases entering the unit from the patient to be returned to him without passing through the soda lime when this is in the circuit. Hence, provided the canister filling is effective, the only carbon dioxide returned to the patient will be from the deadspace between the patient and the T-piece, together with a little carried into the inhalatory tube during exhalation by turbulence and diffusion.

Two units of this type were examined, the Boyle Mark II Circle Absorber and the Gillies Mark III Apparatus. So far as carbon dioxide absorption is concerned, the units are identical in method of operation. Both were tested as completely closed circuits.

1. Boyle Mark II Circle Absorber. Tests on this unit were carried out with the breathing machine running at 20 respirations per minute at a tidal volume of 500 ml, and with a carbon dioxide input of 200 ml per minute (this gave an exhaled concentration of 4½ per cent). Under these conditions, the inhalatory carbon dioxide concentration at the face mask remained between 0.1 and 0.2 per cent for 4½ hours, then rose sharply, due to exhaustion of the soda lime.

In order to assess the effect of carbon dioxide entering the inhalatory tube during exhalation, this test was repeated with the unidirectional valves of the unit removed, and replaced by rubber flap valves inserted close to the T-piece on the face mask. Under these conditions, the inhalatory carbon dioxide concentration at the face mask remained at 0.0 per cent for 4½ hours, reached 0.05 per cent after 4½ hours, and 0.2 per cent after 4½ hours 40 minutes, then rose sharply due to exhaustion of the soda lime.

2. Gillies Mark III Apparatus. Tests on this unit were carried out with the same breathing conditions as for the Boyle Circle Absorber. Two runs were carried out with practically identical results. The inhalatory carbon dioxide concentration remained below 0.1 per cent for 4 hours, reached 0.05 per cent after 4½ hours, and 0.2 per cent after 4½ hours 40 minutes, then rose steadily due to exhaustion of the soda lime.

The Waters Absorber.

In the Waters absorber, provided the soda lime is efficient, the inhaled carbon
dioxide concentration will depend on the amount reinhaled from the deadspace, and hence, in a closed system, on the volume of the deadspace. When the soda lime is partly exhausted, this deadspace will be increased by the intergranular space in the exhausted part of the soda lime, since this first occurs at the proximal end of the canister, as stated by Orton (1952).

Four runs were carried out with the breathing machine running at a respiratory rate of 20 per minute, with a tidal volume of 500 ml and a carbon dioxide input of 200 ml per minute. In these runs, which agreed well, the inhalatory carbon dioxide concentration entering the face mask was effectively zero for \(3\frac{1}{2}\) hours, reached 0.15 per cent, after 4 hours and then rose steadily due to exhaustion of the soda lime, reaching 0.6 per cent in \(4\frac{3}{4}\) hours and 1.0 per cent in 5 hours.

A run was also carried out on a conscious human subject (D.M.S.). The inhalatory concentration entering the face mask remained effectively zero for \(2\frac{1}{4}\) hours, then rose steadily, reaching 0.6 per cent in \(3\frac{1}{2}\) hours and 0.9 per cent in \(3\frac{3}{4}\) hours.

The effect of varying the breathing and other conditions has also been examined. Results qualitatively similar to those of Adriani (1946) were obtained.

It is not generally appreciated that the efficiency of a Waters absorber will depend on the care used in filling the canister. Since the canister is normally used on its side, if the soda lime is not reasonably tightly packed it will settle slightly during use, leaving a path of lower resistance along the top. This effect is an extreme form of the channelling described by Adriani (1946) and by Bracken and Sanderson (1955). The effect of ineffective packing has been described by Robson and Pask (1954). We have confirmed experimentally that there is a serious loss of efficiency and effective life if the canister is not tightly packed. This often occurs if canisters are filled from separate 1-lb packages of soda lime, which may not be quite sufficient.

We have found that there is little relation between the inhalatory carbon dioxide concentration and the concentration in the rebreathing bag. The latter always rises sharply a considerable time before a sharp rise in the inhalatory concentration indicates exhaustion of the soda lime. The reason for this is that further absorption takes place on return through the soda lime, as described by Adriani (1946).

We have also found that there is very little connection between the temperature of a canister and the efficiency of its charge.

The Semi-closed System.

Several publications have appeared on the subject of rebreathing in semi-closed systems (without absorption). Molyneux and Pask (1951) have attempted to analyse mathematically the gas movements in such a system, and have produced gas flow measurements, but no gas analyses, to support their calculations. However, as stated by Domaingue (1951), this work is based on a number of incorrect assumptions, the chief of which is that complete mixing occurs of the gases in the corrugated hose and the rebreathing bag. Mapleson (1954) has deduced a mathematical theory for a number of
systems of this type, which seems very adequate except that no allowance is made for any degree of mixing. However, if due allowance is made for this factor, the theory gives a very good account of gas behaviour in these systems.

Faulconer and Laterell (1949) have drawn attention to suboxygenation which occurs in partial rebreathing, due to oxygen depletion of too low an input flow, and Crowley et al. (1948) indicate that, when using 80 per cent nitrous oxide in oxygen, the total gas input should not be less than 6 litres per minute. Clement (1951), Swartz et al. (1953) and Ruben (1953) have carried out further work on this aspect.

Wynn (1941) states that if the total gas input falls below 5 litres per minute, a dangerous accumulation of carbon dioxide may occur. Hewer (1953) confirms this, and states that the relief valve should be situated as close to the face piece as possible, to reduce deadspace.

Swartz et al. (1953) have carried out some inhalatory carbon dioxide analyses with various systems on unanaesthetized patients. High readings were obtained, even allowing for larger deadspaces, varying from 6 per cent at a gas input of 3 litres per minute to 0.8 per cent at 8 litres per minute. The method of sampling is not stated.

Woolmer and Lind (1954) have carried out some inhalatory carbon dioxide analyses, the results of which, allowing for some mixing, are consistent with the theory of Mapleson (1954).

We have carried out some tests on the Magill attachment on the Boyle apparatus, using our breathing machine. For convenience, the gas input consisted entirely of oxygen. Since the breathing machine does not absorb oxygen, the input flowrate was corrected by adding on the equivalent carbon dioxide flowrate into the breathing machine, assuming a respiratory quotient of unity, since this was judged to be sufficiently accurate for our purposes.

In the first tests, the input flowrate was varied while the tidal volume was kept constant at 500 ml, the respiratory rate at 20 per minute, and the carbon dioxide input at 200 ml per minute. The results are given in table I. Equilibrium was reached in 15 minutes at 2 litres per minute, and in less than 5 minutes at 10 litres per minute input. It was found that variation of the valve setting within the effective range had little effect, so this was neglected.

| Table I
| Magill Attachment
| Variation of inhalatory carbon dioxide concentration with gas input

<table>
<thead>
<tr>
<th>Input flow, l./min</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per cent CO, inhaled</td>
<td>2.7</td>
<td>1.35</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
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</table>

At a flow of 10 litres per minute and a respiratory rate of 20 per minute, the effect of varying the tidal volume was next investigated. On increasing the tidal volume to 1,000 ml and the carbon dioxide input to 400 ml per minute, the inhalatory concentration remained at 0.1 per cent. On reducing the tidal volume to 360 ml and the carbon dioxide input to 145 ml per minute, the inhalatory concentration rose to 0.3 per cent.

A test was next carried out at an input flowrate of 10 litres per minute, with a tidal volume of 500 ml, a rate of 40 respirations per minute and a carbon dioxide input of 400 ml per minute. An inhalatory
concentration of 0.2 per cent was obtained.

Increase of the deadspace between the face piece and the relief valve increased the concentration returned to the patient, as expected.

We have also carried out some tests on the Boyle Mark II Circle Absorber, used as a semi-closed system with the soda lime out of circuit, for comparison purposes. The relief valve on the T-piece was opened. With the tidal volume kept constant at 500 ml, the respiratory rate at 20 per minute, and the carbon dioxide input to the breathing machine at 200 ml per minute, the input flowrate was varied. It was found that slightly higher inhalatory carbon dioxide concentrations occurred with the absorber ether vaporizer turned on, filled with water. The results are shown in table II.

| Table II |
|-----------------|---|---|---|---|---|
|                | Input flow, l./min | 2  | 4  | 6  | 8  | 10 |
| Variation of inhalatory carbon dioxide concentration with gas input |
| Per cent CO₂ inhaled, ether full on | 4.15 | 1.6 | 0.75 | 0.3 | 0.15 |
| Per cent CO₂ inhaled, ether off    | 3.9  | 1.4 | 0.7  | 0.25 | 0.1 |

Under normal conditions, both types of apparatus have similar effects at higher input flows, while at low input flows the circle absorber returns a higher concentration. This is due not only to its greater capacity for surging with pressure changes by virtue of the greater volume between the relief valve and the rebreathing bag (as illustrated by the increased concentrations returned when the ether vaporizer is on), but also to its greater opportunities for mixing of inhaled and exhaled gases at the T-piece by eddy formation.

So far as the effect of change in tidal volume is concerned, it would at first sight appear that our results are in conflict with those of Woolmer and Lind (1954). However, mathematical analysis based on the Mapleson (1954) theory with mixing factor, shows that both sets are consistent with theory. The apparent difference is due to the fact that Woolmer used a deadspace of 150 ml, whereas ours was 300 ml. It would be anticipated theoretically that there would be an increase in inhalatory concentration at low and at very high tidal volumes.

The effect of increase in respiratory rate is due to the fact that at a higher rate the gas input has less effect. However, the gas velocities are greater, so that the resistance to flow is higher, and the relief valve is open for a greater portion of the cycle, allowing more carbon dioxide to escape. Hence the net result is due to opposed influences of these effects.

It would appear that, under normal conditions, provided the relief valve is close to the face mask, physiologically appreciable concentrations of carbon dioxide in the inhaled gases do not occur unless the total gas input to the system falls below 7 litres per minute.

CONCLUSIONS

(1) Any type of circle absorber is an effective means for the prevention of reinhalation of carbon dioxide.

(2) A Waters absorber is an efficient means of removing carbon dioxide, provided the canister is completely filled and the mechanical deadspace (including the intergranular space of the exhausted part
of the soda lime) is small compared with the tidal volume.

(3) A semi-closed system with the relief valve close to the face piece does not return an appreciable concentration of carbon dioxide under normal conditions provided the total input gas flowrate does not fall below 7 litres per minute.

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REFERENCES