OBSERVATIONS OF CARBON DIOXIDE IN CONSCIOUS AND ANAESTHETIZED SUBJECTS USING THE LISTON-BECKER INFRA-RED ANALYSER

WILLIAM G. CULLEN, M.D.,* G. FREDERICK BRINDLE, M.D.,* and
HAROLD R. GRIFFITH, M.D.,* F.R.C.P.(C), F.F.A.R.C.S.*

THE PHYSIOLOGICAL ROLE of carbon dioxide has long been appreciated. The gas is of paramount importance in the control of both the respiration and the circulation. *Normally* the tension of carbon dioxide in the fluids of the body is maintained within *narrow limits* (1).

However, during anaesthesia these narrow limits are certainly not always maintained. In fact, the finding of marked degrees of respiratory acidosis, owing to the build-up of excessive amounts of carbon dioxide during anaesthesia, is now commonly reported (2, 3, 4, 5, 6, 7, 8).

Although carbon dioxide is the prime factor in producing acidosis, the retention of other metabolic waste products during anaesthesia may also contribute to the clinical picture (9). Their significance requires elucidation.

Recently Bourne (10) and others (3, 7, 11), including the authors (12), have reviewed the literature on the effects of an excess of carbon dioxide during anaesthesia.

Some ten years ago the late Kenneth Heard of Toronto said that "the measure of a good anaesthetist is his ability to maintain good oxygenation in his patient" (13). If he were here with us today, I am certain that he would be the first one to modify his definition to include "the avoidance of an accumulation of carbon dioxide and other waste products"

The acquisition of a Liston-Becker infra-red analyser¹ provided us with a practical physical method of analysing the respired gas mixtures for their carbon dioxide content. Our particular sampling cell (the standard cell on Model 16) was found to be most suitable for continuous sampling of respired gases. The content of carbon dioxide of a sample of mixed gases which is passing through the cell is read on an ink-writing recorder in percentages of carbon dioxide. Thus from moment to moment, from breath to breath, from inspiration to expiration, or from even the beginning to the end of either, the actual content of carbon dioxide can be observed on the recorder. This recorder has three speeds which allow it to measure accurately the time factor (i.e., 5, 15, or 30 seconds per centimetre of paper; Fig. 1) The speed can be chosen according to the rate of respiration or the details of pattern desired in the study. Before and after each test, a calibration tracing was obtained by using as a standard a sample of carbon dioxide provided by the manufacturer, for example, 10.1 per cent carbon dioxide and 89.9 per cent oxygen. The range of the recorder was arbitrarily set

*Department of Anaesthesia, Queen Elizabeth Hospital, and McGill University, Montreal.

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FIGURE 1 Ink-writing recorder for the Liston-Becker infra-red analyser

from 0 to 10 per cent carbon dioxide, as we found this to be a convenient range for our observations

We were interested to know how much carbon dioxide was present in the inspired gas, as well as the expired gas, during various (commonly accepted) anaesthetic techniques (19, 20) We had a method of monitoring not only the actual techniques but also the same technique using different gas machines Naturally, absorption methods were first looked upon with a critical eye Then the particular chemical used as an absorber was studied, i.e., various types of lime

Probably the most important part of our study was related to the problem of determining the adequacy of any method of ventilation Spontaneous ventilation (Sp V) was compared with manually controlled ventilation (MCV) and the latter was compared with automatically controlled ventilation (ACV) in so far as the content of carbon dioxide in the respired gases could serve as an index of efficiency

Carbon dioxide accumulation is not confined to any one technique of anaesthetic administration but may occur with most, if not all, techniques (15, 18), for example, the prolonged effects of succinylcholine are probably due to carbon dioxide accumulation (16, 17)

Although most of our observations were made on anaesthetized patients, conscious volunteers were also used to obtain the carbon dioxide patterns Only about fifty such patterns have been obtained, so that this report should only be considered as a preliminary one However, a close study of the available tracings has proven very interesting and may challenge some of our clinical impressions

METHODS OF SAMPLING

I *Expiratory Only*

The Liston-Becker sampling cell is placed in the expiratory circuit of a circle absorption system just as it leaves the Y-connector at the mask or endotracheal tube (Fig 2) The tracing provides a measurement of the carbon dioxide con-

FIGURE 2 The Liston-Becker sampling cell placed in the expiratory circuit for expiratory sampling only

tent of the mixed expired gases. We are particularly interested in knowing the content of the end-expiratory or end-tidal sample, as this value is as close to that of the alveolar air as can be determined. The curve rises to a plateau which is terminated by an additional short rise to a "point" immediately prior to the inspiratory phase (Fig 3). This last "point" on the wave is thought then to represent the alveolar carbon dioxide content (14).

Initially we thought that this method of sampling would be the most accurate way to determine the carbon dioxide content of the end-expiratory sample. However, it seemed that the fresh gases, if entering at a high flow rate, could readily pass through the Y-connector and contaminate the sample in the cell. In addition, if inspiration were assisted or controlled a greater spill-over into the expiratory arm would occur from the inspiratory side. Although such contamination of the sample could readily occur with anaesthetized subjects, it was also possible in conscious ones, even though to a lesser degree.

II *Inspiratory Only*

The Liston-Becker sampling cell is placed in the inspiratory circuit at the inspiratory valve of the machine. It can also be placed next to the "Hico"

FIGURE 3 (Tracing no. 25-2). Tracing obtained during expiratory sampling, showing alveolar carbon dioxide values between 6.7 and 7.5 per cent at the upper limits of the pattern.

detector² when the latter is adjacent to the inspiratory valve. This detector is a simple device introduced by Draper (21) which determines the concentration of carbon dioxide in the inspired mixture, utilizing the acid-base indicator, bromocresol purple.

Tracing no. 6 (Fig. 4) shows the inspiratory pattern obtained with a conscious subject when the degree of absorption of the machine was deliberately changed. The levels of carbon dioxide at which the "Hico" detector changed in colour were recorded.

Indicator Colour				Carbon Dioxide Content
Deep purple	—	Faded	0	0.1 — 0.2 %
Deep purple	—	Faded	0	1.8 — 2.0 %
Purple	—	Very slightly faded	+	3.5 — 3.7 %
Purple	—	Definitely faded	+ +	4.2 — 4.4 %
Clear colour	—	Faded	+ + +	5.6 — 6.0 %
Straw colour	—	Faded	+ + + +	8.4 — 9.0 %

Thus it can be seen that a carbon dioxide level of over 3.5 per cent was necessary to produce even slight fading in this indicator and at least 4.0 per cent was needed to produce a change in colour readily recognized by several observers. Although the efficiency of the "Hico" detector may, at first, not seem adequate, we have clinically found the device to be a helpful indicator of rising carbon dioxide in the inspiratory circuit. At levels of carbon dioxide producing colour

²Available from the Ohio Chemical Co. of Canada.

FIGURE 4 (Tracing no. 6-1). Inspiratory pattern showing the carbon dioxide values in percentages corresponding to changes in colour of the "Hico" detector. "Abs" means absorber. Tracing starts at the right with the absorber turned one-third off.

change in this indicator, there may still be very little other clinical evidence of carbon dioxide accumulation. On the other hand, when this indicator dye does fade, we should realize that the levels of carbon dioxide have already risen considerably.

Recently the British Oxygen Company have introduced a somewhat similar chemical carbon dioxide analyser, but we have not had an opportunity to monitor its efficiency.

III. Tidal: Inspiratory and Expiratory

During these studies we have found tidal sampling to be the most practical as it presented fewer difficulties, and moreover, the most interesting and helpful patterns.

For tidal sampling, the Liston-Becker sampling cell is connected directly to the mask or the endotracheal tube, thus allowing *all* the respired gases to pass through the analyser (Fig. 5). A comparison between the inspiratory and expiratory levels of carbon dioxide is always available. Consequently, most of our tracings are those obtained by tidal sampling.

TECHNIQUES WITH CARBON DIOXIDE ABSORPTION

I. Gas Machines

The efficiency of carbon dioxide absorption by some type of lime in a gas machine was evaluated in both *conscious* and *anaesthetized* subjects. Nine indi-

FIGURE 5 The Liston-Becker sampling cell placed in the circuit for tidal sampling of inspiratory and expiratory gases

vidual machines of various manufacturers were studied using the same brand of lime in each (Heidbrink, Foregger (circle and to-and-fro types), Boyle, Loos, Marrett, and Reserve Midget)

We were initially intrigued by the rapidity with which the pattern would change when the absorber was turned off, and again when it was turned on. With the very next breath of the subject, after absorption was stopped, the inspiratory carbon dioxide level sharply rose and continued to rise with each succeeding breath. At the same time, the expiratory level very gradually rose, with the result that the two levels soon approached each other. The tracing was then only a shallow wavy line at a level of about 9-10 per cent, in the conscious cases.

It was an interesting finding that none of the conscious volunteers would tolerate over 10 per cent carbon dioxide. One subject, on several tests, signalled to have the absorber turned on only when the recorder indicated exactly 10 per cent carbon dioxide (24). When the absorber was turned on, the levels rapidly returned to normal (Fig. 6).

Harbord found "alveolar" carbon dioxide levels above 7 per cent in a high proportion of patients, after making over 300 observations (22, 23).

We were surprised to find the "alveolar" levels in several of our volunteers, when breathing either air or oxygen, to be between 7.0 and 8.0 per cent (Fig. 7). There is probably a considerable variation in subjects.

Thus there is very good evidence of the efficiency of this method of carbon dioxide control. In general, all the common machines used by anaesthetists (at

FIGURE 6 (Tracing no. 3-5). Carbon dioxide tracing of conscious volunteer with absorber off until the pattern reached the peak which represents 10 per cent carbon dioxide. The lower points of the pattern represent inspiratory levels and the upper points represent expiratory levels of carbon dioxide.

least the particular ones tested) have quite efficient absorption units. However, when a single test pattern was obtained from several machines, changing every minute or two from one to another, quite a variation was obtained. When monitoring absorption efficiency in this way, the inspiratory carbon dioxide levels were most significant. Although most of the patterns were obtained with the subjects breathing oxygen with or without anaesthetic gases, we did obtain a few tracings (not illustrated) when conscious subjects inspired predetermined concentrations of carbon dioxide.

Although most of the absorption units provided consistently comparable patterns indicating efficiency, two units repeatedly provided tracings indicative of a higher degree of efficiency. One machine indicated by F in the tracings produced an inspiratory pattern indistinguishable from that of room air, or from that obtained with a non-rebreathing valve (Fig. 7).

On the other hand, one unit persisted in producing a definitely higher inspiratory level of carbon dioxide, but it also gave the conscious patient definite evidence of resistance during inspiration and expiration (Figs. 7 and 8). Further trials with other specimens of this "brand" of machine should be done.

II. Absorption Lime

Three different "brands" of lime, provided for anaesthetic machines, were used in these tests. The tracings indicated that each specimen of fresh lime proved to be a good absorber of carbon dioxide when initially used.

FIGURE 7 (Tracing no. 17). Carbon dioxide pattern of conscious volunteer, changing frequently from one gas machine to another. F-2, one machine with closed circle system with absorption; D-1, another machine with closed to and fro system with absorption; JV, one machine with non-rebreathing valve; LV, another machine with non-rebreathing valve. All, except D-1, produced very good inspiratory levels of carbon dioxide.

It has been reported by Gibbon *et al.* that lime required frequent changing (every 20-30 minutes) when ventilation was automatically controlled, because of the increase in minute volume. Our short experience with automatically controlled ventilation in this study seemed to bear out this requirement. However, the efficiency of one brand of lime seemed to decline after 2 or 3 minutes with the inspiratory levels, slowly creeping up thereafter. Another brand maintained its efficiency at the initially good level after at least 45 minutes of automatically controlled ventilation (Fig. 9). Thus there may be some variation in the efficiency of lime. We have, as yet, no observations on the efficiency of various limes after prolonged periods of use or after periods of rest. Very wet lime was found to be less efficient than the standard product (Fig. 10).

TECHNIQUES WITHOUT CARBON DIOXIDE ABSORPTION

In England there has been for many years, and in Canada more recently, a technique with no absorption of carbon dioxide but rather an intentional partial rebreathing. It is usually referred to as a semi-closed to-and-fro method. It should not be confused with the to-and-fro Water's absorption unit which can also be used in a semi-closed circuit.

This English inhaler consists of a mask, expiratory valve, single breathing tube, and a small bag attached to the machine.

FIGURE 8 (Tracing no. 16-1). Carbon dioxide pattern of conscious volunteer with absorption using various limes and various machines and a slow recorder. The lower points of the pattern (inspiratory levels) change with the efficiency of the lime or the machine. As the absorber is on or off the level changes with each breath. Rate of respiration was 10 (as indicated).

It is a very practical unit for the administration of nitrous oxide, oxygen and ether, or trichlorethylene.

In 1946 A. Charles King repeats (25) that "rebreathing is not only economical but physiologically sound in that it prevents the patient suffering from carbon dioxide deficiency." Our tracings, with all methods, indicate that there is never any need of being concerned about carbon dioxide *deficiency* but rather about an excess.

Some carbon dioxide patterns were obtained in the conscious patient with oxygen, as well as in the anaesthetized patient with nitrous oxide and oxygen, with or without trichlorethylene (T.C.E.). The Liston-Becker cell was placed at the mask between the latter and the expiratory valve. One tracing was obtained from a patient having sigmoidoscopy under pentothal- N_2O-O_2 -T.C.E. anaesthesia with the above technique, using a five-litre bag. The total gas flow was varied from 0.5 litres to 15.0 litres on the machine unit designated J. After a pentothal induction (300 mg.), a mixture of 6 litres N_2O plus 2 litres O_2 was started with a small amount of T.C.E. When the total flow was at least 8 litres, quite a good pattern was obtained. However, when it was increased to 9, 10, 11, 13, 14, and 15 litres, no appreciable improvement occurred. But when the total flow was decreased to 7, 6, 5, 4, 2, 1 and $\frac{1}{2}$ litres, a very definite upward shift in the inspiratory levels occurred at every step, especially below 6 litres.

FIGURE 9 (Tracing no. 10-6). Pattern in anaesthetized subject comparing M.C.V. (manually controlled ventilation) with A.C.V. (automatically controlled ventilation on Jefferson ventilator); M.C.V. in various degrees of pressure and rhythm from no. 2 to 10% on tracing. Note the better pattern after A.C.V. is started. Lime used over 45 minutes.

This tracing (not illustrated) is complicated by an increase in respiratory rate unrelated to raised carbon dioxide levels but rather due to T.C.E. This rapid shallow respiration can be shown to be very inefficient when considering carbon dioxide elimination.

Fig. 11 shows the effects of this method when using only oxygen, in a conscious volunteer. The conscious experienced subject soon objects to the expiratory resistance in the circuit. He is forced to expire against positive pressure a good deal of the time because of the high inflow of gases and the resistance in the expiratory valve. If the bag is suddenly emptied he will quietly and comfortably breathe directly to and from the bag. The tracing will immediately show a sharp rise in carbon dioxide levels and as the pressure builds up, the subject will eventually blow open the expiratory valve with an inner sense of great relief; this is only to be followed soon by another build-up of pressure and carbon dioxide.

If a non-rebreathing valve is used in place of the expiratory valve in such a circuit, the expiratory resistance is immediately removed and the carbon dioxide pattern simulates that obtained with the Liston-Becker cell open to room air (Fig. 7).

VENTILATORY EFFECTS ON CARBON DIOXIDE LEVELS

Since it has been shown (24) that ventilation bears a very direct relationship to the alveolar and arterial levels of carbon dioxide, we cannot stress too

FIGURE 10 (Tracing no. 3-6). Pattern in conscious volunteer, to be compared with Fig. 8. At the right the tolerance level of 10 per cent carbon dioxide is reached, while respiratory rate is only 20 per minute. Very wet line does not return inspiratory levels to normal in a comparable span of time, whereas regular line is effective.

emphatically the need for adequate ventilation. In clinical anaesthesia, whether you are watching the movements of the chest and abdomen, or feeling the rate, regularity, and force of expiration on the palm of your hand, or seeing or feeling the movements of the breathing bag, how can you judge the adequacy of the ventilation? Do you satisfy yourself by the colour of the skin or blood? Do you compare the ventilation of your anaesthetized patient with that of the same patient you may have observed sleeping in bed on the previous evening? If so, is the extent of the ventilation during sleep adequate for the same patient when anaesthetized? There is no useful clinical evidence of carbon dioxide retention.

It has been known for some time that the total ventilatory minute volume necessary for the prevention of respiratory acidosis in the anaesthetized patient is in excess of that required by the normal unanaesthetized individual. A value two or three times the resting normal values may be required to maintain a normal arterial carbon dioxide tension (15).

Thus we were keenly interested to see the effects on the carbon dioxide tracing of clinically adequate spontaneous ventilation, manually controlled ventilation, and automatically controlled ventilation. The latter was obtained with the Jefferson Ventilator (Fig. 9).

These tracings show very clearly that the automatically controlled ventilation proved consistently uniform inspiratory and expiratory levels, for example, 0.5 per cent and 6.0 per cent respectively. Each time the ventilation was

FIGURE 11 (Tracing no. 5-6). Conscious volunteer, using semi-closed technique without absorption, breathing oxygen.

FIGURE 12 (Tracing no. 8-3). Anaesthetized subject showing the lower inspiratory levels when A.C.V. is compared with M.C.V., reading from right to left.

FIGURE 13 (Tracing no. 14-1). Anaesthetized subject showing effects of various types of ventilation, reading from right to left. Respiratory rate is 30 per minute during spontaneous ventilation while A.C.V. rate is 24.

switched over to manual control, the efficiency depreciated very definitely, in spite of the most clinically efficient manner in which any of us could perform the method. Possibly we are not gifted with "educated hands." Thus we were soon convinced of the superior results obtained with the automatic ventilator. No doubt the effects on the circulation are equally superior, especially when the positive and negative pressures are suitably adjusted to the particular patient (5) (Fig. 12).

Expiratory levels during spontaneous ventilation appear much higher than those obtained by automatically or manually controlled ventilation (Fig. 13). Does this mean that this particular subject is better able to eliminate carbon dioxide from his alveoli by spontaneous ventilation than we are able to do for him by manual or mechanical means? We cannot answer this problem but it leaves a challenging observation with us.

CONCLUSIONS

1. Carbon dioxide levels in the inspired gas mixture can rise very suddenly and persistently. What is more dangerous and more common is the unsuspected chronic accumulation of carbon dioxide which may develop insidiously. This will jeopardize the ability of the patient to eliminate carbon dioxide (1); especially when he is already depressed by anaesthetic drugs. Gray reminds us that in the anaesthetized subject concentrations of carbon dioxide as low as 5 per cent may lose their stimulatory effect and be converted to a depressing one (24).

2. The need for some simple device for detecting carbon dioxide during anaesthetics should be emphasized.

3. Gas machines providing efficient carbon dioxide absorption are essential for closed circuit anaesthesia. The manufacturer should provide good evidence of such efficiency.

4. The value of a non-rebreathing technique to eliminate carbon dioxide has been clearly shown (26, 27, 28, 29).

5. Anaesthetic techniques which involve any rebreathing or the addition of carbon dioxide should be critically challenged.

6. Effective alveolar ventilation, in addition to oxygenation, should be the insistent objective of every anaesthetist. Should we adopt the motto "V for Ventilation"?

7. Further studies of carbon dioxide levels in the respired gases, as well as in the arterial system, are essential to the progress of anaesthesia.

Professor W. R. Spurrell recently concluded a discussion of carbon dioxide as follows: "We want to put more faith in the respiratory centre, to cherish it and nourish it but not to flog it, to guard its blood supply and its oxygen supply, to regulate the pressures within the respiratory tract and then the centre will look after the carbon dioxide problem itself" (23).

RÉSUMÉ

Le rôle du gaz carbonique a longuement été discuté. Le gaz carbonique joue un rôle de premier ordre dans le contrôle de la respiration aussi bien que dans celui de la circulation. Chez l'individu normal, la tension du gaz carbonique dans les liquides de l'organisme ne présente que de légères variantes (1).

Toutefois, au cours de l'anesthésie, il peut arriver que les limites normales soient dépassées. En fait, on rapporte couramment de nos jours des cas d'acidose respiratoire marquée, due à l'accumulation, au cours de l'anesthésie, de grandes quantités de gaz carbonique (2, 3, 4, 5, 6, 7, 8).

Bien que le gaz carbonique soit le principal facteur dans la production de l'acidose, la rétention, au cours de l'anesthésie, de certains autres produits du métabolisme peut aussi contribuer à réaliser ce tableau clinique (9). Mettons en lumière l'importance de leur rôle.

L'appareil Liston-Becker, analyseur à infra-rouge, nous a permis d'analyser, par une méthode physique pratique, les atmosphères respirées et de connaître leur contenu en gaz carbonique.

Ainsi nous avons pu observer à tous les instants, à toutes les respirations, à l'inspiration et à l'expiration, le pourcentage de gaz carbonique présent.

Nous étions intéressés à connaître le pourcentage de gaz carbonique dans l'air inspiré aussi bien que dans l'air expiré au cours des différentes techniques anesthésiques en usage courant (19, 20).

Notre méthode ne nous a pas permis seulement d'évaluer les techniques actuelles mais également d'évaluer les différentes machines à anesthésie. Naturellement, nous avons commencé par les méthodes d'absorption dans un but critique. Après, nous avons étudié les différentes substances employées pour absorber le gaz carbonique, c'est-à-dire la variété des sortes de chaux.

La plus grande partie de cette étude, probablement, est consacrée à l'évaluation de l'efficacité de chacune des méthodes de ventilation. Nous avons comparé la

ventilation spontanée (Sp. V.) à la ventilation contrôlée à la main (M.C.V.), celle-ci à la ventilation contrôlée automatiquement (A.C.V.), en prenant comme index d'efficacité, le pourcentage de gaz carbonique dans l'atmosphère expirée.

Conclusions

1. Le taux de gaz carbonique dans les mélanges de gaz inspirés peut s'élever rapidement et de façon continue. Ce qu'il y a de plus dangereux et de plus fréquent, c'est l'accumulation chronique et insoupçonnée du gaz carbonique qui peut survenir insidieusement. Elle peut compromettre, pour le malade, la possibilité d'éliminer son gaz carbonique (1), surtout s'il est déprimé par les agents anesthésiques. Gray nous rappelle que, chez des sujets anesthésiés, des concentrations de gaz carbonique aussi basses que 5 pour-cent peuvent perdre leurs effets stimulants et acquérir des effets dépresseurs (24).

2. Il faudrait insister sur la nécessité de trouver un procédé simple pour doser le gaz carbonique au cours des anesthésies.

3. Pour faire de l'anesthésie en circuit fermé, il est essentiel d'avoir des machines assurant une absorption efficace. Les manufacturiers devraient pouvoir prouver l'efficacité d'absorption de leurs machines.

4. La valeur de la technique de non-réinspiration pour éliminer le gaz carbonique a été clairement démontrée (26, 27, 28, 29).

5. Il faut se défier des techniques d'anesthésie où il existe une certaine ré-inspiration, ou encore, où il y a une addition de gaz carbonique.

6. En plus de l'oxygénation, la ventilation alvéolaire efficace devrait être l'objectif constant de tous les anesthésistes. Ne devrions-nous pas adopter le motto "V pour Ventilation"?

7. Il est essentiel, pour le progrès de l'anesthésie, que soit poursuivie l'étude des taux de gaz carbonique dans l'air inspiré aussi bien que dans le sang artériel.

Récemment, à la suite d'une discussion sur le gaz carbonique, le Professeur W. R. Spurrell concluait ainsi: "Nous voulons augmenter notre confiance dans le centre respiratoire, nous voulons en prendre soin et le nourrir et non pas le fouetter, nous voulons lui conserver ses réserves de sang et d'oxygène, nous voulons régler les pressions dans les voies respiratoires et, alors, le centre respiratoire s'occupera lui-même du problème du gaz carbonique" (23).

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