Proceedings of the Royal Society of Medicine

Vol. 46
365

Section of Anæsthetics

President—M. D. NOSWORTHY, M.A., M.D.

[*January* 2, 1953]

The Role of Carbon Dioxide in Anæsthesia [*Summary*]

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Dr. R. P. Harbord, Mr. S. Parnell and **Dr. A. B. Eastwood:** *Spontaneous pulmonary ventilation related to carbon dioxide elimination.*—The carbon dioxide content of gaseous mixtures from the depths of the lungs has been correlated with pulmonary ventilation during 35 relatively minor operations, mainly herniorrhaphies, performed under thiopentone anæsthesia with Flaxedil in all cases and with pethidine in 11.

Only oxygen was inhaled through a large sized cuffed endotracheal tube connected to a Waters' canister filled with fresh soda lime, and with the reservoir bag replaced by a bellows whose movements were recorded. This bellows was similar to the one described by Benson *et al.* (1951).

The subjects' ages varied between 22 and 63 years and were mainly between 30 and 50 years. During the period of observations the average dose of thiopentone was slightly over 1 gramme, and that of Flaxedil 114 mg. The dose of pethidine ranged from 25 to 100 mg. The aim was to maintain tidal volumes similar in extent, judged by bag movements, to what was frequently allowed by anæsthetists for this type of operation.

Blood loss was minimal but was not measured.

Gases were obtained during spontaneous breathing from the depths of the lungs by a rapid manual chest compression at the end of an expiration, and while the anæsthetic apparatus was temporarily cut off at the endotracheal mount, an evacuated gas sampling tube was opened through a rubber bung in the suction limb of a Cobb's adaptor. The forced expiratory volume was recorded. Blood samples were taken anaerobically from the radial artery at this time.

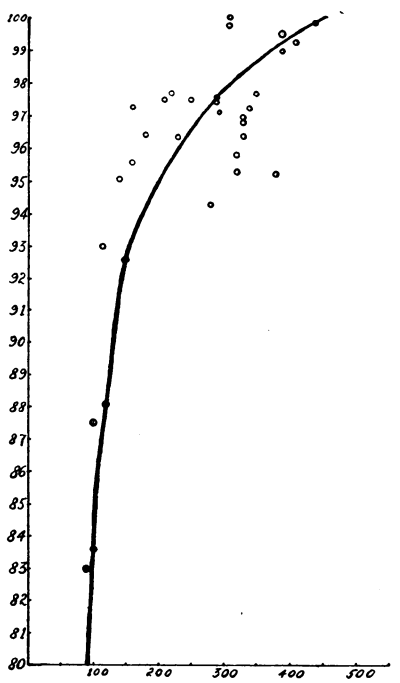


FIG. 1.—Abscissæ: percentage of original sample. Ordinates: volume displaced in millilitres.

The sampling process has been investigated to determine whether alveolar or dead space gases had been obtained. A model glass trachea was constructed, 2 cm. in diameter, fitted at one end with a rubber bag, which could be distended and then released to discharge a given volume of gases of a known carbon dioxide content. Through the upper end was passed a cuffed endotracheal tube with a Cobb's adaptor; the dead space, 110 ml., approximates to that of the sampling system of the average patient.

Because of the lack of respiratory data for the anæsthetized patient, the results have been related to existing values for the normal conscious subject at rest. For respiration rate the limits are from 14 to 18 per minute; for tidal volume, 350 to 500 ml. Hence the limits for minute volume are calculated to be from 4·9 to 9 litres per minute, and if the dead space is assumed to be 150 ml., the effective or alveolar minute volume limits lie between 2·8 and 6·3 litres per minute. The average tidal volume of patients was calculated from the arithmetical average of all the inspirations in the minute before sampling the lung gases. The carbon dioxide content of alveolar air in the normal subject at rest has been taken to vary between 4·7 and 6·4%.

RESULTS

Fig. 1 shows that when 140 ml. or more pass through the model trachea, previously containing air, 90% of the carbon dioxide content could be recovered at the Cobb's adaptor, and 95% when the volume exceeded 200 ml.

The duration of the whole sampling process in patients was less than 5 seconds in over 70% of the examples.

A comparison between the carbon dioxide tension in the lung gases and the calculated tension in arterial blood, practically simultaneously drawn, showed that an agreement of plus or minus 5 mm.Hg could be obtained in one-third of the examples, the remainder demonstrating a higher tension in the lung gases.

Fig. 2 shows the extent of pulmonary ventilation before sampling on 108 occasions, the extent of the forced exhalations and the carbon dioxide percentage of the samples.

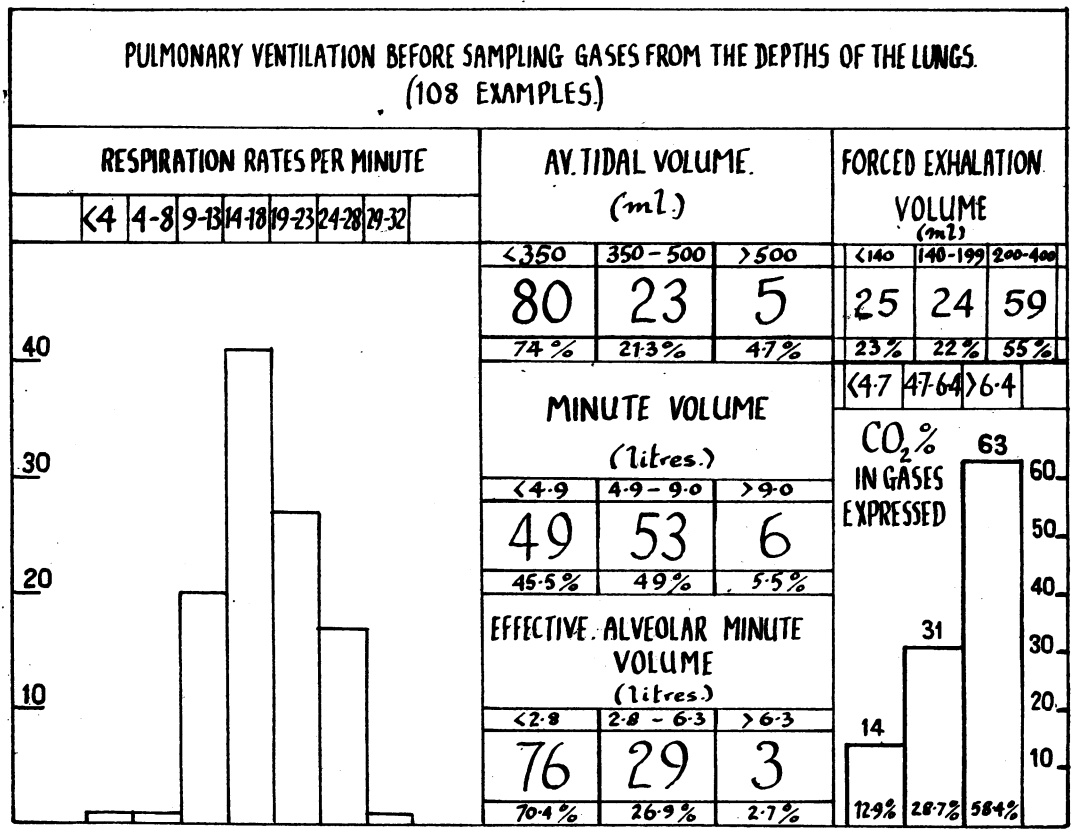


FIG. 2.—Table summarizing results.

The relation between the average tidal volume and the percentage of carbon dioxide in the lung gases is shown in Fig. 3, the examples being chosen for uniformity in respiratory pattern.

After respiratory depression one pattern showed a return to normality of tidal volume more rapidly than that of the carbon dioxide content of lung gases—changes of from 190–370 ml. of tidal volume corresponding with carbon dioxide percentage changes from 8·6 to 7·7%—measured during nineteen minutes of recovery of ventilation after extreme depression.

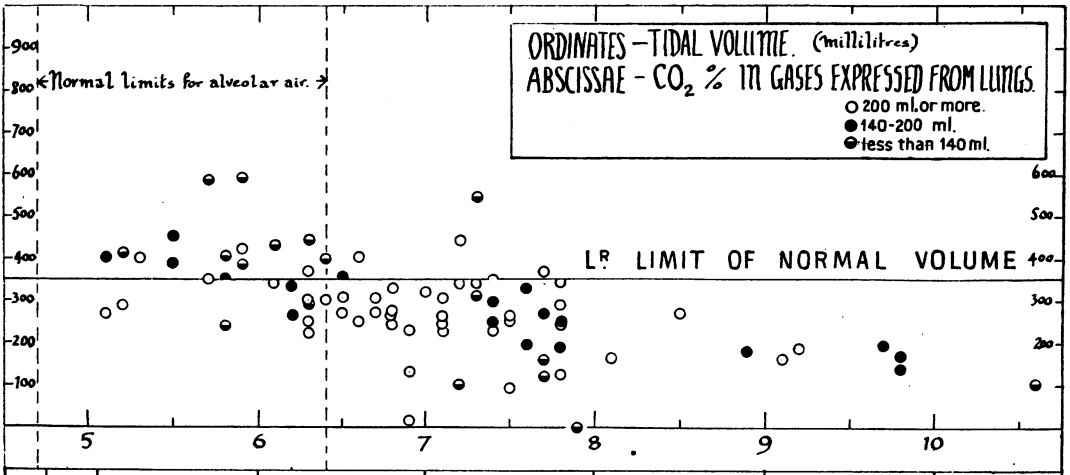
The longest period during which samples of the lung gases had values between 8 and 9% was nineteen minutes. All the patients recovered.

The classical signs of carbon dioxide excess were not observed although particular care was taken to observe changes in the facial colour and the state of the skin and the superficial vessels.

Bleeding from cut surfaces did not appear to be increased even when the carbon dioxide percentages in the lung gases were above the usual alveolar limits.

DISCUSSION

The results show that when the average tidal volume is between 350 and 500 ml., the percentage of carbon dioxide in the lung gases lies mainly within the limits found in the alveolar air in conscious subjects at rest.



NO	AV. TIDAL VOL	RANGE	MEAN	S.D.	C.V.	TOTAL
22	350-600	5·1 - 7·7	6·1	0·72	11·7 %	81
41	200-349	5·1 - 8·5	6·9	0·69	10·0 %	
18	0 - 200	6·9 - 10·6	8·3	1·06	13·3 %	

FIG. 3.—The distribution of carbon dioxide percentage in gases expressed from the lungs in relation to tidal volume.

Since the interval between the end of expiration in patients and the opening of the tonometer was generally less than 5 seconds, carbon dioxide accumulation during the sampling process was probably negligible as is indicated by the work of Dubois *et al.* (1952).

The experiment with a model trachea suggests that when more than 200 ml. are forced out from the lungs by a rapid chest compression, then the carbon dioxide content of the gases will be a slight underestimate of the alveolar value.

The reason for the difference between the calculated arterial carbon dioxide tension in the blood and the tension in the lung gases is not clear. This problem is the subject of a separate investigation.

Haldane and Priestley measured the tidal volume changes in conscious man breathing carbon dioxide mixtures, and found that when the alveolar carbon dioxide changed from 5·6 to 6·6%, the tidal volume increased from 673 to 2,104 ml.

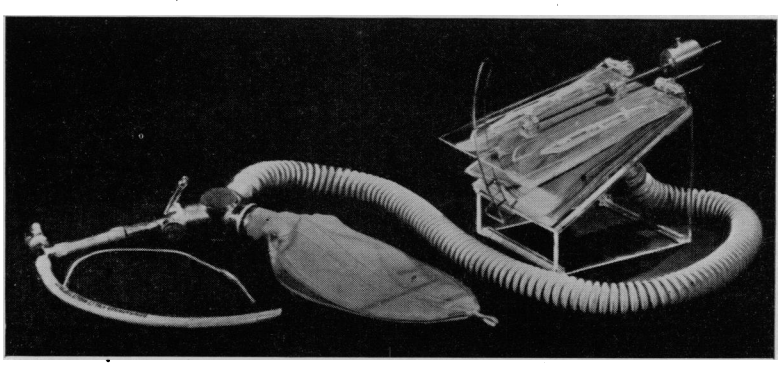


FIG. 4.—Apparatus for the visual measurement of tidal volume.

Using a method which slightly underestimates alveolar carbon dioxide it has been shown that when the gases from the depths of the lungs contained from 6·9 to 10·6% of carbon dioxide, the tidal volume varied between apnœa and 200 ml. Such is the order of change in the anæsthetized state.

Pulmonary ventilation should be assisted under anæsthesia when the tidal volume falls below 350 ml. An instrument for measuring tidal volume is described in the appendix.

Carbon dioxide excess is an insidious state in the unconscious subject and may persist when the tidal volume is above 350 ml. if the previous ventilation has been below normal.

Because patients have recovered despite high percentages of carbon dioxide (8–9%), in the gases from the depths of the lungs lasting for periods up to nineteen minutes, it does not follow that this state is one from which no harm will accrue. Clearly, more work is indicated to settle this point. It appears that where respiratory depression is allowed carbon dioxide will accumulate, probably more so than has generally been realized, and may even decide the issue unfavourably in gravely ill patients.

Appendix

A tidal volume recorder has been constructed on a similar principle to the one used for recording pulmonary ventilation but smaller and with a lever operating against a scale calibrated to each 100 ml., and supported on a plastic stand. The recorder may be attached to standard apparatus by a large bore 3-way tap as shown in Fig. 4.

Acknowledgment[1]

We wish to thank Mr. L. Byrom for his technical assistance in the laboratory, and also the surgeons of the United Leeds Hospitals for their co-operation. Our thanks are also due to Mr. H. R. Noltie of the Physiology Department (University of Leeds), for much valuable advice.

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[*This paper will be published in full elsewhere*]

Dr. B. G. B. Lucas and Dr. E. H. Milne: The role of carbon dioxide in anæsthesia cannot be discussed without a prior knowledge of the mechanisms which maintain the acid-base balance in the blood at a normal level in the conscious subject. The hydrogen-ion concentration depends on the ratio of free carbonic acid to that combined as bicarbonate and rapid alteration in the ratio may be effected by the "chloride shift" whereby more base is made available, and by the extreme sensitivity of the respiratory centre to changes in pH resulting in adjustments in ventilation and excretion of carbon dioxide via the lungs. During surgical operations the acid-base balance is disturbed because of the effect of the anæsthesia on the respiratory centre and on the dynamics of respiration; hence some degree of carbon dioxide retention occurs. Accordingly, the acid-base changes that occur during surgery have been studied by estimating the carbon dioxide tension in the circulating blood during operations. The carbon dioxide tension was calculated from measurements of the total carbon dioxide content and pH of the blood (Peters and Van Slyke, 1931). The carbon dioxide content was measured by a micro-volumetric method using capillary blood (Scholander and Roughton, 1943). The pH was recorded electrometrically with a potentiometer and glass electrode, the latter being incorporated in a special syringe into which blood was drawn anaerobically under mercury. To facilitate blood gas analysis anæsthesia was maintained with thiopentone or pethidine, with tubocurarine or Flaxedil for relaxation. All cases were intubated and the carbon dioxide absorption technique was used whenever controlled or assisted ventilation was performed. 159 cases have been investigated, 80 being for abdominal surgery, 62 for thoracic surgery and the remainder limb operations in which the effect of posture was deliberately studied.

In the series of abdominal cases operated on in the supine position there was always a rise of carbon dioxide tension if the patient was allowed to breathe by himself. If vigorous controlled ventilation was carried out from the start of the operation, the tension could be kept within normal limits, but only in the presence of a perfectly free airway. It was impossible to ventilate any patient adequately if he were in the Trendelenburg position, in spite of attempted overventilation. The effect of posture on ventilation was deliberately studied on 17 patients undergoing minor limb operations. In the Trendelenburg position the rise of carbon dioxide tension was found to be proportional to the degree of tilt. In the lateral position the carbon dioxide tension increased, particularly if the table were broken. In the thoracic cases the increased carbon dioxide tension due to the lateral position and to breaking the table rose further when the chest was opened because of the unavoidable inadequate ventilation, being most marked in operations where a lung was deliberately deflated, e.g. an œsophagectomy, or when a bronchial occluder was used (Fig. 1).

A number of effects were observed on the anæsthetized patient when there was a respiratory acidosis. The systolic blood pressure rose during major surgery, but fell abruptly immediately post-operatively

[1]Part of the expenses for this work was defrayed by the Association of Anæsthetists of Great Britain and Northern Ireland.

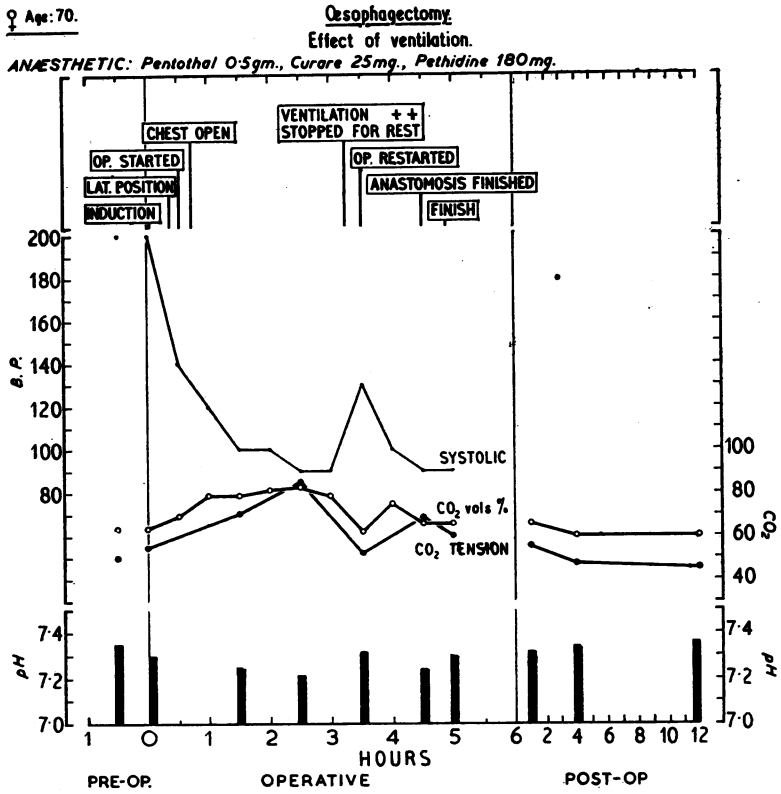

FIG. 1.

and was accompanied by signs of circulatory collapse. The dosage of thiopentone necessary to maintain an even plane of anæsthesia was increased. Operative reflexes were more active and recovery time delayed. Whether the delay in recovery was due to the increased amount of thiopentone used or to a diminished rate of breakdown of thiopentone in the body was not discovered. In upper abdominal surgery a respiratory acidosis was associated with hiccup.

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PETERS, J. F., and VAN SLYKE, D. D. (1931) Quantitative Clinical Chemistry. Baltimore.
SCHOLANDER, P. F., and ROUGHTON, F. J. W. (1943) *J. biol. Chem.*, **148**, 573.

[*This paper will be published in full elsewhere.*]

Dr. Ronald Woolmer: Most anæsthetists are aware that carbon dioxide accumulation must be harmful, but the harm it causes is often not apparent, and the importance of avoiding underventilation is therefore not self-evident. We can very seldom say, with any confidence, that a patient's recovery has been prolonged or complicated because of carbon dioxide retention during anæsthesia. It would be a help to us all if we could be told that certain specific bad effects are causally related to carbon dioxide retention, so that they always appear when it has occurred, and never when it has not.

Dr. E. J. Moran Campbell: The functional dead space of an apparatus is not the same as its volume. The shape is important; where it contains an expanded portion gases can pass through in a stream without mixing with the main volume, thus reducing the dead space. A constriction can have a similar effect. In such circumstances the functional dead space also depends upon the volume rate of gas flow. Even with an apparatus consisting of tubing of uniform bore the functional dead space is probably always less than the volume.

When considering the effect of an apparatus on the ventilatory exchanges, in addition to dead space the resistance must be taken into account at all levels of ventilation occurring under the conditions in which it is used. Cain and Otis (1949, *J. Aviat. Med.*, **20**, 149) have shown that added resistance to respiration causes a rise in alveolar pCO_2. The resistances they used are probably much greater than those occurring in anæsthetic machines. Their subjects, however, were conscious and not curarized. During anæsthesia lower levels of resistance may suffice to cause CO_2 retention.

It is instructive to work out pH changes in terms of actual hydrogen-ion concentration. A change of 0·3 of a pH unit may mean a halving or a doubling in hydrogen-ion concentration. A rise of 0·3–0·4 in the pH has been recorded during anæsthesia (Dundee, J. W., 1952, *Brit. med. J.*, ii, 893).

The results reported by the opening speakers show that respiratory acidosis occurs during anæsthesia as carried out by modern methods, and may have deleterious effects. I would like to recommend caution before going to the other extreme and producing respiratory alkalosis by vigorous controlled respiration.

In this connexion I would like to make three observations:

(1) It is much easier to produce alkalosis by passive overventilation than by active overventilation.

(2) Volume for volume an unbuffered increase in the CO_2 content of the arterial blood produces less change in pH than a decrease. For instance, if we take 50 c.c. and 2·5 c.c. as the combined and free CO_2 content per 100 ml. blood, and the pH as 7·4, an increase of 1 c.c. free CO_2 per 100 ml. lowers the pH by 0·15 unit, whereas an equal decrease in the free CO_2 content causes a rise of 0·2.

(3) Overventilation has been shown to have profound physiological effects, including: tetany; decreased cerebral blood flow (Kety, S. S., and Schmidt, C. F., 1946, *J. clin. Invest.*, **25,** 107); and loss of vasomotor tone (Dale, H. H., and Evans, C. L., 1922, *J. Physiol.*, **56,** 125; Seevers, M. H., Stormont, R., Hathaway, H. R. and Waters, R. M., 1939, *J. Amer. med. Ass.*, **113,** 2131). The latter workers do not attach much importance to their findings, but the rise in pH they deliberately produced is less than that recorded by Dundee in routine practice.

It is obviously difficult, even with exact measurements, to assess the importance of a single variable such as the pH or pCO_2 during the complex situation caused by anæsthesia and surgery. In view of this, and our present limited knowledge of the effects of such gross changes as have been reported, it is obviously desirable that procedures which cause them should be used with caution.

Dr. Cyril F. Scurr said that he was disturbed by Dr. Lucas's concluding remarks, which implied that certain cases had a high CO_2 level despite artificial ventilation. He had always thought that the elimination of CO_2 depended simply on a washing-out process, and that provided the tidal air was adequate and the dead space within reasonable limits carbon dioxide elimination should be satisfactory.

Concerning the possible ill-effects of raised carbon dioxide tension, it was well known that cardiac arrhythmias could thus be caused, and he had often seen arrhythmias disappear following the institution of effective ventilation.

A recent case might suggest another possible adverse effect of carbon dioxide accumulation. In this patient, a child, prolonged paralysis was encountered following the administration of decamethonium iodide. Respiratory depression had persisted for three hours, during which time oxygen was administered continuously. At the end of this time carbon dioxide retention was suspected, and he undertook for five minutes energetic ventilation of the child through a soda-lime absorber. The absorber promptly became very hot, presumably indicating the elimination of considerable CO_2. At the end of this ventilation the respiration of the child immediately returned to normal. It seemed possible that the carbon dioxide led to a condition simulating the curarized state.

Search through literature fails to reveal any work on the effects of CO_2 at the myoneural junction, but it would be very surprising if these high CO_2 levels were entirely without effect there.

Dr. E. K. Brownrigg: Estimation of the alveolar carbon dioxide tension in patients anæsthetized by the Bullough technique would be an interesting study in view of the quiet breathing and reduction of capillary oozing. Would this be a practicable extension of the investigations which have been described?

Hiccup is unquestionably a complex phenomenon. In the conscious patient this distressing symptom can sometimes be treated successfully by inhalations of 5% carbon dioxide.

Hiccup can apparently occur in the fully curarized patient under anæsthesia: this suggests an action of the diaphragm independent of the phrenic nerves.

Dr. Harbord, in reply to Dr. Brownrigg, said that the same procedure to obtain gases from the depths of the lungs could be adopted in patients under anæsthesia using the Bullough technique. As nitrous oxide is soluble in 10% caustic soda, which is used to absorb carbon dioxide in the Haldane apparatus, a saturated solution of caustic soda, as suggested by Prime, F. J., (1950, *Brit. J. Anæs.*, **22,** 162) would have to be used.