ANALYSIS OF RESPIRATORY ACIDOSIS DURING ANESTHESIA*

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THE OCCURRENCE OF respiratory acidosis as an accompaniment of thoracic surgical procedures has been demonstrated by numerous investigators.[2, 3, 9-12, 15, 18, 28, 29] It is generally agreed that impaired alveolar ventilation is responsible for carbon dioxide retention, but there has been considerable disagreement in regard to the underlying cause or causes of diminished alveolar ventilation. Beecher[2-4] stressed the harmful effects of the lateral position and gave results to indicate that acidosis does not occur in the supine or prone (Overholt) position with ether anesthesia.[3, 4] Acidosis occurring in the prone position, however, is reported by Etstein.[10] Maier[15] not only found a lowered pH in his patients before they were turned, but also noted a marked degree of acidosis in some cases during abdominal operations done in the supine position. This respiratory acidosis is believed to be due to the depressant action of ether by Taylor and Roos,[29] the open pneumothorax by Gibbon and associates,[12] and rebreathing of CO_2 in the anesthesia system in the presence of a low tidal volume by Stormont.[28]

This study was undertaken in order to determine if respiratory acidosis occurred under the conditions of our anesthesia, and perhaps to clarify factors responsible for it. The majority of patients chosen were those undergoing thoracic surgery; position, opening of the pleura, assisting of respiration, etc. were carefully analyzed. These studies were also carried out in a smaller group of general surgical patients to study CO_2 elimination with the patient in the supine position.

METHODS

Anesthesia. All anesthetics were administered by physician anesthetists of the Department of Anesthesiology at the Medical College of Georgia, or by members of the resident staff under their supervision. The usual premedication was pentobarbital sodium 50 to 100 mg., and scopolamine, 0.3 to 0.4 mg. subcutaneously. Induction was usually carried out by an intravenous injection of evipal sodium, 350 to 500 mg., and syncurine, 2.8 to 4.0 mg. An endotracheal tube with cuff was inserted and anesthesia continued, using the circle absorption method with a N_2O-O_2 mixture for the first few minutes, and then anesthesia maintained with C_3H_6-O_2. During the last 10 to 15 minutes of anesthesia, N_2O-O_2 and a semi-closed system were employed. Manual assistance to respiration was used when thought necessary by the anesthetist.

This general procedure was altered in certain cases. Occasionally N_2O was not used in the initial period. In Case 10, a to and fro system was employed. In five cases an intravenous injection of evipal was administered, followed by 20 to 40 mg. of succinylcholine. In three cases a face mask was used, induction in two of these being carried out by intravenous administration of 200 to 250 mg. of 2.5 per cent solution of pentothal sodium, and in the other by cyclopropane alone.

Time of Sampling. To facilitate interpretation of results the procedure was arbi-

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TABLE I. *Summary of Mean Arterial pCO_2 Values and Statistical Analysis of Results.*

	No. of Values	Mean Arterial pCO_2 mm. Hg	Standard Error	Statistical Significance
Normals	34	41.3	0.26	Significantly less than all values during anesthesia $p < 0.001$
Stage I	(35)			
A No N_2O	14	69.0	4.5	
B N_2O	21	149.6	7.5	Significantly greater than Stage I A. $p < 0.001$
Stage II	(83)	98.3	3.4	Significantly greater than Stage I A. $p < 0.001$ Significantly less than Stage I B. $p < 0.001$
A Chest Cases	61	100.1	3.5	
B Non-chest Cases	22	93.5	8.0	Not significantly different $p = 0.424$
C No N_2O	25	92.1	5.3	
D N_2O	58	101.0	4.0	Not significantly different $p = 0.194$
Stage III	14	175.9	3.7	
Stage IV (Average 1.5 minutes after extubation or mask removal)	10	79.2	6.7	
Stage V (Average 10 minutes after extubation or mask removal)	16	57.5	2.7	Probably significantly less than Stage IV. $p = 0.003$

trarily divided into five periods. (1) The first 25 minutes after induction of anesthesia; (2) the "middle" period of anesthesia when the patient was maintained on cyclopropane; (3) the latter portion, after the switch to N_2O-O_2 and a semi-closed system and before extubation or mask removal; (4) within five minutes after extubation or mask removal, and (5) five to 28 minutes after extubation or mask removal. Blood samples were not obtained during every period in all cases. In most instances an additional sample was obtained either before or several days after the operation, these results being referred to as "normals."*

Chemical Analysis. Blood samples were withdrawn anaerobically from an indwelling arterial needle placed in the brachial artery immediately after induction of anesthesia. The syringe was lightly oiled and the sides wet with a 50-50 solution of heparin sodium and 4 per cent sodium fluoride in physiological saline. A few drops of this solution plus a small amount of mercury for mixing were left in the syringe. The blood was immediately placed on ice until analyses could be completed.

Duplicate analyses for total CO_2 and O_2 content were performed, using the method of Van Slyke and Neill,[30] checks of 0.3 volumes per cent being required. CO_2 content of whole blood was converted to plasma CO_2 content.[31] No correction for the presence of the anesthetic gases (N_2O and C_3H_6) was required.[19] The oxygen capacity was determined by oxygen analysis after equilibration of the blood with room air for 20 minutes, or in some instances calculation from the hematocrit.[20]

The CO_2 tension was determined in duplicate by the method of Riley *et al.*[22] The maximal variation of duplicate samples was $\pm$ 6 mm. Hg in the range below 100 mm. Hg, and although above this occasionally checks to only 10 mm. Hg were obtained, much closer checks in both ranges were the rule. On the unanesthetized patient the analyst's alveolar air was used, but during the anesthesia under conditions of high oxygenation a sample of the patient's expired air was obtained from the expiratory tube of the anesthetic apparatus to make the bubble for equilibration. The pCO_2 was converted to volumes per cent by multiply-

* These "normals" were used after it was found that they differed very little from samples analyzed immediately prior to induction of anesthesia.

ing by 0.0696[7] and the bicarbonate was obtained by subtracting this value from the total CO_2 content.

The pH of plasma was then calculated by the Henderson-Hesselbach equation:[21]

$$pH = 6.11 + \log \frac{(BHCO_3)-}{H_2CO_3}$$

The whole blood buffer base was calculated from the plasma bicarbonate and the pH, using the nomogram of Singer and Hastings.[24]

Ventilatory Studies. On 15 cases the respiratory minute volume was obtained using an apparatus described by Maloney *et al.*[16] In one case[29] a Kreiselman bellows[14] equipped to write on a drum was used to record total ventilation. The effective alveolar ventilation was calculated by the formula: effective alveolar ventilation = (tidal air − dead space) × respiratory rate; 150 cc. was arbitrarily used as the dead space in all patients.

RESULTS

Forty-four patients, 31 chest and 13 non-chest cases, were studied during operation. The thoracic cases included two pneumonectomies, seven lobectomies, seven thoracoplastics, one division of a patent ductus arteriosus, one Blalock operation for Tetralogy of Fallot, four thoracotomies, four esophageal resections, two cardioplasties, two diaphragmatic hernia repairs, and one mediastinal tumor. The non-thoracic cases were two thyroidectomies, three gastric resections, one colon resection, three resections of mandible, maxillae, or nose; one total abdominal hysterectomy, one vaginal hysterectomy and right salpingo-oophorectomy, and two operations on the lower extremity. Chest operations were done in the lateral position, general surgery in the supine position, one gynecological procedure in the Trendelenburg position, and the other in Trendelenburg and lithotomy positions. In one orthopedic case the patient was supine while in the other the prone position was used.

Table I is a summary of the mean pCO_2 values during different periods of anesthesia with a statistical analysis. The pCO_2, rather than the pH, was used to indicate the degree of acidosis. We feel justified in doing this because (1) the pCO_2 was determined directly, (2) in no case did the bicarbonate level significantly alter the pH and (3) the arterial pCO_2 level is a reflection of the efficiency of alveolar ventilation because it equals the mean of the entire range of alveolar CO_2 pressure existing in different parts of the lung and at different moments in the ventilatory cycle.[23]

The mean pCO_2 for the "normals" was 41.3 mm. Hg with a range of 28.6 to 54.9. The mean pH was 7.39 with a range of 7.36 to 7.51.

CO_2 retention occurred in all cases. In the majority the maximal pCO_2 was 100 mm. Hg, and in many cases a peak of 175 to 200 mm. Hg was reached. All initial pCO_2 values were elevated well above normal. The earliest sample, taken five minutes after beginning of the injection of evipal sodium (Case 35), was 167 mm. Hg. Many cases reached a high level within a few minutes after induction, with values decreasing gradually during the procedure, while in other cases there was a tendency for CO_2 retention to increase during the procedure. The sudden initial increase in arterial pCO_2 evidently was related to decreased ventilation associated with respiratory depression as the result of evipal and syncurine or succinylcholine. Approximately the same elevation in pCO_2 occurred with syncurine as with succinylcholine. However, in Stage I a significant rise in the pCO_2 occurred when N_2O was given. The mean pCO_2 without the gas was 69.0 mm. Hg, with the gas 149.6 mm. Hg, the difference being 80.6 mm. Hg. This difference is statistically significant ($p < 0.001$).

The mean arterial pCO_2 for Stage II was 98.3 mm. Hg. There was no significant dif-

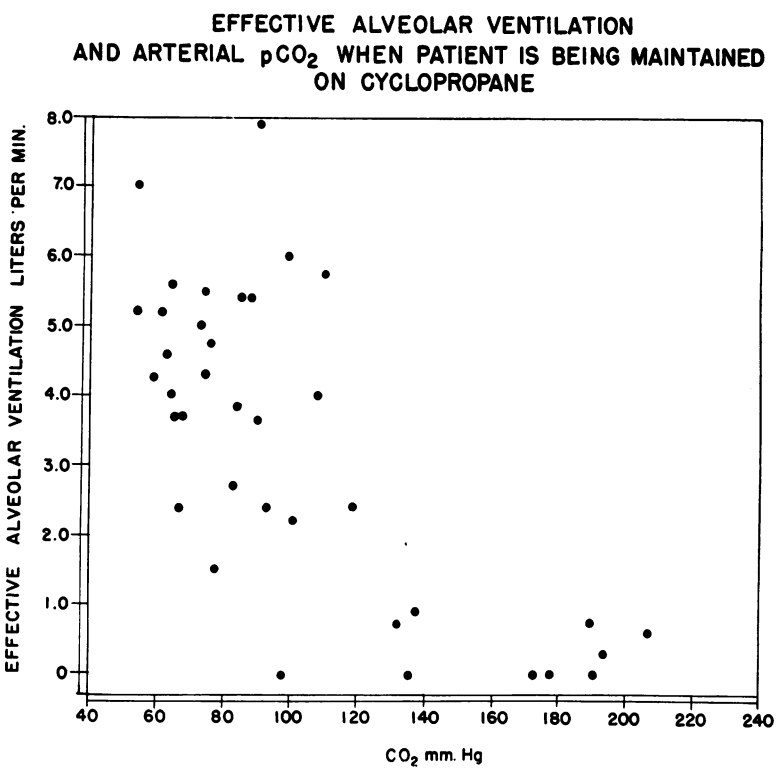

FIG. 1. Effective alveolar ventilation and arterial pCO_2 when patient is being maintained on cyclopropane.

ference ($p = 0.424$) in the degree of acidosis in the non-chest cases and the chest cases and in those inducted with or without N_2O ($p = 0.194$). It is noted that a significant decrease ($p < 0.001$) in the mean pCO_2 value occurred in Stage II when compared with the value in N_2O inducted cases of Stage I, whereas a significant increase ($p < 0.001$) occurred in those not inducted with this gas.

In Stage III the mean pCO_2 reached 175.9 mm. Hg, the highest at any time during the anesthesia. It was observed that 14 of the patients studied had greatly elevated pCO_2 soon after changing to N_2O and a semi-closed system. On more careful analysis it was seen that in eight of these cases there was a mean increase of 112 mm. Hg from a mean of 12 minutes prior to the change to a mean of 14 minutes after the change. The explanation for this sudden increase in acidosis is not clear, but may possibly be related to the effect of N_2O. At the time of the study this sudden change was not anticipated, and samples were not taken with that in mind.

A dramatic and significant decrease ($p < 0.001$) to a mean pCO_2 of 79.2 mm. Hg occurred immediately after extubation or mask removal (Stage IV). This is shown in detail for ten cases in Table II. A further decrease to a mean of 57.5 mm. Hg took place in Stage V. This latter drop is probably significant ($p = 0.003$). Values for both Stage IV and Stage V remain well above the "normal" level ($p < 0.001$).

It is interesting to note that there is no significant difference in the mean pCO_2 in Stage I in the patients inducted without N_2O and the mean pCO_2 in Stage IV and Stage V ($p = 0.194$ and 0.028 respectively).

The Trendelenburg, lithotomy and lateral positions, particularly when rests are used, are the operating positions which tend to

interfere most with ventilation.[5, 27] Slocum[25] *et al.* agreed with Beecher[2-4] that the lateral position is responsible for the increased CO_2 tension during operation. Undoubtedly ventilation is impaired in this position but we were unable to corroborate his findings, and our study is in accord with that of Maier,[15] and indicates that the pCO_2 rises early before the patient is turned, and often decreases during the operation. Also with patients in the supine position the increase in pCO_2 was of the same order. There was no greater CO_2 accumulation in our patients operated on in the Trendelenburg (Case 41), or Trendelenburg and lithotomy positions (Case 46).

In three cases arterial pCO_2 was studied immediately prior to opening the pleura and a few minutes afterwards. There was a mean increase of 15 mm. Hg. In a fourth case ventilation was assisted during this period of opening the pleura and immediately thereafter, and arterial pCO_2 decreased from 113 mm. Hg to 83 mm. Hg. The fact that it was necessary to keep the lungs partly deflated in order that the operation could proceed was no doubt of greater respirtory significance than merely opening the pleura.

The effects of assisting respiration reported in the literature have been variable. Gabbard and associates[11] found that acidosis could be prevented by manual assistance from the beginning of anesthesia. Maier[15] agreed that vigorous assistance may offset any further increase in CO_2 tension. Beecher[2] was able to lower the tension in one patient but not in another. Using a mechanical respirator, Gibbon[12] was unable to prevent an acidosis. In our series four patients were studied from this standpoint. Respiration was assisted vigorously in all cases and pCO_2 was decreased in all. In one patient (Case 22) after 15 minutes assistance, the arterial pCO_2 decreased from 125 mm. Hg to 88 mm. Hg. In a second case (26) after 60 minutes assistance arterial pCO_2 decreased from 98 to 65 mm. Hg, with the calculated effective alveolar ventilation increasing from 0 to 3.7 liters per minute. In a third instance (Case 29) 18 minutes of assistance produced an effective alveolar ventilation increase from 1.5 to 11.6 liters per minute with a decrease in pCO_2 from 113 to 83 mm. Hg. A decrease in pCO_2 from 66 to 54 mm. Hg with an increase in effective alveolar ventilation from 3.7 to 7.0 liters per minute produced by 70 minutes of assisted respiration occurred in Case 32. In no case, however, was arterial pCO_2 reduced to normal levels by manual assistance. More vigorous assistance over longer periods of time might have resulted in lowered pCO_2 values, but such assistance might have resulted in a decreased cardiac output,[8] or might have inflated the lung to the point of interfering with the surgical procedure.

In many cases the buffer base was decreased slightly, presumably due to an increase in fixed acids. This evidence of a slight degree of metabolic acidosis has been noted by others.[4, 10, 29] Our study agrees with that of Etstein[10] that the height of the pCO_2 does not correlate with the increased fixed acids.

In these patients end-expiratory CO_2 values[13] were within normal limits, indicating that the soda lime cannister was efficient in removing CO_2, and was not responsible for retention of CO_2. Under conditions of the anesthesia the reduced minute volume probably did not efficiently wash out the dead space, so that the sample could not be regarded as valid alveolar air samples. Nevertheless, the fact that there was no accumulation of CO_2 in the ventilating gas indicated that the high blood CO_2 was not due to failure of CO_2 absorption from the air.

Arterial oxygen saturation was within normal limits during all stages in the majority of patients. This obviously was the result of high oxygen tension of the anesthetic mixture of gases.

It has been demonstrated previously that poor alveolar ventilation is responsible for respiratory acidosis during anesthesia.[26] It has also been shown that breathing pure oxygen has no appreciable effect on ventilation of normal individual.[6, 17] It is known also that in certain types of pulmonary insufficiency, notably pulmonary emphysema, oxygen administration causes retention of CO_2, often with deleterious results.[1] Four patients were studied to evaluate the effects of sedation, position and oxygen inhalation on the acid-base state. Two patients (#12 and #17) had recently healed lung abscesses, and a third patient (#18) had moderately advanced pulmonary tuberculosis. The functional status was within normal limits in all three patients. Sedation, lateral position and oxygen administration produced no significant change in pH, bicarbonate and pCO_2. A fourth patient (#15) had had a total thoracoplasty for tuberculous empyema. He had a small residual empyema space and the contralateral lung was markedly emphysematous. His resting arterial pCO_2 was 48 mm. Hg. After breathing pure oxygen for 22 minutes the pCO_2 had increased to 66 mm. Hg and at the end of 34 minutes had reached 76 mm. Hg, the pH being 7.22, and the buffer base unaltered. Subsequently, Cases 15 and 18 were studied during operation, and the pCO_2 in the former case reached much higher levels than in the latter, the maximum value being 209 mm. Hg 99 minutes from induction of anesthesia. During the procedure the anesthesiologist had difficulty maintaining adequate ventilation, and during the immediate postoperative period the blood pressure fell to 70-80 systolic. The fall in blood pressure was possibly related to the sudden drop in arterial pCO_2,[9] which decreased 133 mm. Hg from a sample taken 14 minutes prior to extubation to one taken 10 minutes after extubation. In such a patient with poor alveolar ventilation as a result of emphysema one expects CO_2 to be eliminated ineffectively, because of impairment of intrapulmonary mixing of inspired air with alveolar air. Apparently, alveolar ventilation was further impaired by the depressant effects of the anesthetic agent. Also the high oxygen concentration within the anesthetic system satisfies O_2 requirement, decreases the stimulus for respiration in the carotid sinus and aortic body, and produces further hypoventilation. Under the conditions of anesthesia pulmonary insufficiency is produced in the normal lung. This is a selective pulmonary insufficiency resulting from hypoventilation as a result of the depressing effects of the anesthetic agent and high O_2 concentrations of the system. The depth of respiration is reduced and a compensatory increase in rate usually occurs so that total ventilation may be within normal limits. However, with the decrease in tidal volume the physiological dead space represents a greater proportion of the total ventilation at the expense of the effective alveolar ventilation. The ratio of physiological dead space to tidal volume is inversely proportional to the efficiency of alveolar ventilation in elimination of carbon dioxide. The transport of gases across the pulmonary membrane is unaltered. If alveolar ventilation is already impaired, as in emphysema, this disturbance is accentuated in the anesthetized state.

TABLE II. *Ten Cases to show Dramatic Decrease in Arterial pCO_2 after Tube or Mask is Removed.*

Case #	Time in minutes prior to extubation or mask removal	CO^2 mm Hg.	Time in minutes after extubation or mask removal	CO^2 mm Hg.
32	7	145.5	2	86.3
33	10	129.1	1	84.0
35	5	135.6	1	59.0
36	9	241.4	1	96.5
37	7	187.0	1	117.3
38	12	236.1	1	104.8
39	10	183.7	1	59.6
41*	9	157.2	2	69.8
42	8	178.7	2	62.2
43*	1	144.7	3	52.7
Average	7.8	173.9	1.5	79.2

*Mask.

In 15 patients simultaneous alveolar ventilation and arterial pCO_2 were determined at different periods of anesthesia. As anticipated and as has been previously demonstrated[8] an inverse relationship existed, the poorer the alveolar ventilation, the greater the arterial pCO_2. Figure 1 illustrates this relationship in Stage II.

SUMMARY

1. A study of 44 patients undergoing major surgical procedures revealed evidence of respiratory acidosis in all cases.

2. The lateral position played no role in the production of acidosis, there being no significant difference in the degree of acidosis between the patients studied in the supine and those studied in the lateral position.

3. Inefficiency of CO_2 absorbing system was eliminated as a causative factor by finding normal values in end-expiratory (not alveolar) CO_2.

4. Acidosis increased on opening the pleura. This increase could be avoided by manual assistance at this time. Vigorous manual assistance would reduce the arterial pCO_2 but these values were not reduced to normal.

5. In the early period of anesthesia arterial pCO_2 was higher when N_2O was used. All cases were shifted to a semiclosed system with N_2O near the end of anesthesia, and at this time pCO_2 increased greatly. No explanation is offered for this relationship, and further study is needed before N_2O can be definitely implicated as a causative factor.

6. After the end of anesthesia a precipitous decrease in arterial pCO_2 occurred within 1.5 minutes but after ten minutes values still were elevated to 16 mm. Hg above normal values.

7. An inverse relationship was established between alveolar ventilation and arterial pCO_2.

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