Acid-base monitoring of open-heart surgery

H. G. MORGAN, R. R. OGILVIE, AND W. F. WALKER

*From the Departments of Pathology and Surgery of the University of St. Andrews
at the Royal Infirmary, Dundee*

SYNOPSIS The techniques and interpretation of acid-base studies on patients undergoing open-heart surgery with extracorporeal circulation are described. The 'normal' range and duration of changes in 35 surviving patients are given; these were essentially of respiratory rather than of metabolic origin, being a respiratory alkalosis induced by the anaesthetist before perfusion, and a respiratory acidosis after assisted respiration was stopped. Gross metabolic acidosis was seen only where clinically severe complications had occurred.

Open-heart surgery in man using extracorporeal circulation is now a common procedure in the United Kingdom, but until recently there has been little published information from the British centres on the biochemical responses to such operations. A detailed study in the immediately post-operative period was therefore carried out to define the range and duration of acid-base and other biochemical changes which might be expected (Walker, Morgan, Breckenridge, Watt, Ogilvie, and Douglas, 1963). This was felt to be particularly opportune now that the techniques and equipment are more standardized.

Previous studies on extracorporeal circulation had shown the main biochemical response to be an alteration in blood pH, in part 'respiratory' and in part 'metabolic' in origin. Especially dangerous was metabolic acidosis, which occurred some three hours after perfusion (Ito, Faulkner, and Kolff, 1957), attributed mainly to low rates of perfusion or low cardiac output with consequent tissue hypoxia and the accumulation of acid metabolites. Although improved techniques have diminished the incidence of metabolic acidosis, problems in acid-base metabolism still occur and require careful analysis and treatment. In this paper we present our further experience on acid-base monitoring of open-heart surgery.

METHODS

Details of the earlier part of our study are given by Walker *et al.* (1963), and our subsequent work has confirmed the utility of our approach as briefly detailed here. Blood samples are drawn anaerobically from an indwelling arterial cannula (used for monitoring of pressures) into a siliconed heparinized (5,000 u. per ml.) syringe, static fluid having first been cleared from the cannula.

Fluoride is not used (Siggaard-Andersen, 1961). Samples are taken every 10 to 15 minutes during perfusion, immediately after, and usually hourly thereafter. Blood is at once expressed gently into a 4 ml. bottle until this is completely full (for CO₂ content) and most of the residue into a standard bottle (for haematocrit and ordinary chemistry) leaving 1 to 2 ml. in the syringe, which is capped until used to determine the pH of whole blood.

Estimation of the whole-blood pH is carried out within five to 10 minutes, because of the drop in pH that occurs with time. Clinically negligible falls, under 0.02 pH, occur over about 30 minutes if the blood is kept at room temperature, and over one to two hours if kept in iced water, but the pH falls by about 0.001 per minute at 38°C.

The pH meter mainly used is that of the British Electronics Instruments Ltd. no. 48A. Blood is sucked into a capillary electrode immersed in a water-bath accurately controlled at 37.5°C., as the pH of whole blood alters by 0.015 pH per °C. (Faulkner, 1961). The electrode is frequently calibrated with at least two standard phosphate buffers, 6.840 and 7.416 (Mattock, 1959, 1961; E.I.L. booklet) or 7.382 (Bower, Paabo, and Bates, 1961) to a maximum difference of 0.02 pH, all estimations being at least in duplicate, with standardized equilibration time. Buffers and rinsing isotonic saline are also kept at 37.5°C., and no air is sucked through the electrode. No corrections are made for whole blood as against plasma (Severinghaus, Stupfel, and Bradley, 1956a and b) nor for temperature unless hypothermia had been deliberately induced (Severinghaus, 1959).

The plasma CO₂ content is unaffected by the temperature of separation (Severinghaus *et al.*, 1956a) and is estimated by the volumetric van Slyke apparatus, without correction for the dilution by heparin or for any nitrous oxide. Paraffin, in which CO₂ is highly soluble, was not used (Gambino, 1961a).

By use of a nomogram (Singer and Hastings, 1948; Davenport, 1958) with the two key values for pH and CO₂ content, figures for buffer base, change in buffer base (Δ B.B.; 'base excess'), 'standard bicarbonate', and the

partial pressure of CO_2 (pCO_2) are derived. The pCO_2 , in mm. of Hg, may also be calculated, aided by the table of Milch, Bane, and Roberts (1957), from the formula $\text{pCO}_2 = \text{CO}_2 \text{ content} / (\alpha(1 + \text{antilog } \text{pH} - \text{pK}'))$ where the solubility factor $\alpha = 0.030$ and $\text{pK}' = 6.10$. These nomograms and calculations are only valid when the patient's temperature is about 38°C . and the haemoglobin is saturated with oxygen.

The convenient and portable Danish Radiometer apparatus is now also being used.¹ With this, blood pH is read directly and again after equilibration of two further blood samples with gases at known pCO_2 values. From these readings and the nomogram of Siggaard-Andersen and Engel (1960) one can easily derive the actual pCO_2 and the base excess, together with any other desired indices (Astrup, Jørgenson, Siggaard-Andersen, and Engel, 1960). pCO_2 can also be measured directly by the Severinghaus electrode (Woolmer, 1959; Gambino, 1961b) but we have no experience of this electrode.

INTERPRETATION OF INDICES

There is no accepted terminology for acid-base studies (Singer and Hastings, 1948; Elkington and Danowski, 1955; Astrup *et al.*, 1960; Robinson, 1961; Creese, Neil, Ledingham, and Vere, 1962). Our use of some terms must therefore be described.

'Acidosis' is an increase, or tendency to increase, in the hydrogen ions of the blood, with an inverse change in pH. 'Alkalosis' is the converse. Alterations in blood pH are the resultant of two quite distinct causes, 'respiratory' and 'metabolic', defined by changes in carbon dioxide tension and buffer base respectively. Thus $\text{pH} = \text{pK}'$ (a constant + log base/acid. Despite some vagueness, the terms respiratory and metabolic are clinically useful in diagnosis and therapy.

Blood 'carbon dioxide tension' is affected chiefly by the excretory function of the lungs, and expressed as ' pCO_2 ', the partial pressure in mm. of Hg or as α ' pCO_2 ', in mMol./l.; the normal values are 40 and 1.2 (0.03×40) respectively. A raised pCO_2 indicates a respiratory acidosis.

The 'buffer base' of the blood is altered by 'metabolic' acids and bases, and is the sum of the buffer anions, normally about 46 mEq./l. It consists mainly of bicarbonate and proteinate, and so varies with the haematocrit (by 0.42 mEq. per 1 g. of Hb per 100 ml.); because of this it is also often expressed as a variation from a normal of zero ($\Delta \text{B.B.} = \text{change in buffer base}$; 'base excess', positive or negative). The recent neologism 'negative base excess', used to describe the degree of metabolic acidosis, is better replaced by 'base deficit'. Total buffer base is not appreciably affected by pCO_2 changes, (until

'compensatory' or secondary metabolic changes ensue) but the distribution of its components varies considerably, such that the bicarbonate rises with a high pCO_2 and vice versa; this of course affects the CO_2 content. For example, with a pCO_2 of 80 mm. Hg, a severe respiratory acidosis, the blood pH will be about 7.18 and the CO_2 content about 32 mMol./l. without any 'metabolic' change (Fig. 1, point A).

The ' CO_2 content' (total CO_2) in mMol./l. consists essentially of the sum of bicarbonate (about 95%) and dissolved carbon dioxide (αpCO_2) in the plasma of blood collected and spun anaerobically: changes in its amount cannot be used alone to distinguish between respiratory and metabolic upsets, but together with the blood pH can be used to derive any acid-base term with the aid of an appropriate nomogram. We have found that of Davenport useful for a quick clinical appreciation (Fig. 1). Thus a qualitative and quantitative assessment can be made of respiratory (pCO_2) and metabolic

FIG. 1. A rapid evaluation of the respiratory and metabolic components of acid-base status is made by plotting a point from pH and CO_2 content determinations. The respiratory component, pCO_2 , is then obtained by following the appropriate curved line, the heavy black line being the normal of 40 mm. Hg. The metabolic component, change in buffer base, is obtained by the vertical distance from the other heavy line, which represents the normal bicarbonate values of buffer base with changing pCO_2 . Point A is an acute severe respiratory acidosis (CO_2 content 32 mMol./l., pH 7.18, pCO_2 80 mm. Hg) with no change in buffer base. Point B is from the fourth set of data in Fig. 5 (pH 7.32, CO_2 content 16.6 mMol./l., and pCO_2 therefore 31 mm. Hg); this represents a moderate metabolic acidosis with a fall of 7 mEq. in buffer base and a respiratory alkalosis. (After Davenport, 1958.)

¹British agents, V. A. Howe & Co. Ltd., 46 Pembridge Road, London W.11.

(buffer base) components, which, taken carefully in context with the clinical situation and other data, can lead to appropriate action. For example, tracheostomy may be needed in acute respiratory acidosis (high $p\text{CO}_2$, normal buffer base, high CO_2 content), whereas in severe metabolic acidosis (low buffer base, low CO_2 content), as well as treatment of the cause, intravenous sodium bicarbonate can be given quantitatively (as a first approximation the dose could be mMol./l. of base deficit times the extracellular fluid volume in litres. The amount eventually needed depends upon clinical response, to allow for a continuing cause and because intracellular pH changes are largely unknown).

'Plasma bicarbonate' ('actual bicarbonate') is found by subtraction of dissolved CO_2 from the CO_2 content in mMol. per l. , *e.g.*, using normal arterial values, CO_2 content (25.2) less $\alpha p\text{CO}_2$ ($0.30 \times 40 \text{ mm. Hg} = 1.2$) = bicarbonate (24). 'Standard' bicarbonate is the above under standardized conditions of CO_2 tension, *i.e.*, $p\text{CO}_2$ of 40 mm. Hg at 38°C . and with the blood fully oxygenated; it is merely proportional to buffer base, with similar inter-

pretation in representing only the metabolic component of any acid-base change and does not vary with $p\text{CO}_2$ as does CO_2 content. The ' CO_2 -combining power' of plasma is an obsolete technique (see Fig. 40 of Davenport, 1958) but the CO_2 -combining power of whole blood is identical with standard bicarbonate.

Secondary or compensatory changes can occur to primary alterations in either $p\text{CO}_2$ or buffer base, *e.g.*, the respiratory alkalosis from overbreathing of diabetic metabolic acidosis, which tend to restore the pH to normal. At times it may not be possible to distinguish between a secondary change and a mixed disturbance except by clinical judgment.

The use of simple concentration units of hydrogen ions, like other electrolytes, has been convincingly advocated in place of the inverse logarithmic or pH scale (Huckabee, 1961; Campbell, Dickenson, and Slater, 1963); these units are millimicro-equivalents or nano-moles per litre, *i.e.*, $\text{mEq.} \times \text{one million}$, and the normal range is 36 to 44. The main drawback to this terminology is lack of familiarity.

FIG. 2. Data from 35 patients before, during, and after extra-corporeal circulation. Values are from arterial samples except for the 'next day' results, when venous blood was used. The principal change is a respiratory acidosis in the phase of recovery.

FIG. 4. Case 1. Changes in acid-base indices.

The mean pattern of the changes in acid-base balance in 35 surviving patients showed four phases (Fig. 2). In the first, while the patient was under anaesthesia but before perfusion, a raised blood pH and lowered $p\text{CO}_2$ indicated a respiratory alkalosis from hyperventilation deliberately produced by the anaesthetist.

FIG. 3. This correlation between pH and $\log p\text{CO}_2$ changes emphasizes that the principal cause of pH change was respiratory and not metabolic.

During the period of extracorporeal circulation the indices were essentially normal, with a tendency to a lowered $p\text{CO}_2$ from gaseous exchange in the heart-lung machine. After perfusion, but while the patient was still under assisted respiration, the mean CO_2 tension ($p\text{CO}_2$) was normal, but a slight rise both in pH and CO_2 content (and thus in buffer base) indicated a slight metabolic alkalosis.

In the fourth phase, that of recovery, the most constant finding was a high $p\text{CO}_2$ and lowered pH, occurring soon after assisted respiration was stopped, viz., a respiratory acidosis. This gradually returned towards normal by late evening or the following day. The parallel rise in CO_2 content must not be misinterpreted as due to any metabolic change but is due here to an altered physico-chemical equilibrium between the two main components of buffer base (bicarbonate and proteinate) induced by the primary change in dissolved carbon dioxide (Elkington and Danowski, 1955; Davenport, 1958 and Fig. 1). Total buffer base was in fact unchanged, and therefore base excess also remained constant.

The complication which we had feared initially, severe metabolic acidosis, was not seen in this group of patients who survived operation, but did occur in patients who died. This absence of metabolic acidosis (Fig. 3) is presumably due to adequate perfusion rates, absence of severe anoxia, and maintenance of normal circulation by intensive care, including monitoring of blood pressure. It should be emphasized that these patients had relatively uncomplicated types of congenital cardiac disease with short perfusion times.

FIG. 5. Case 2. Changes in acid-base indices.

Individual variations in the usual acid-base response produced certain problems. Case 1, a 28-year-old woman, had an atrial septal defect with an unusual form of anomalous pulmonary venous drainage (Fig. 4). This was unrecognized at operation and the defect was closed, placing a great strain on the return of blood from the lungs. A slight to moderate fall in buffer base (metabolic acidosis) and rise in $p\text{CO}_2$ (respiratory acidosis) combined to cause a considerable fall in $p\text{H}$ during the following 10 hours, when, despite surgical relief of the obstruction and then tracheostomy, gross metabolic acidosis developed in association with anoxia and circulatory failure.

A second patient, a boy of 9, had closure of an atrial septal defect with relief of pulmonary valvular stenosis (Fig. 5). In the immediate post-perfusion phase he had a low blood $p\text{H}$ of mixed aetiology, a metabolic acidosis (fall in buffer base of 7, to 38 mEq./l.) and also respiratory alkalosis (a low $p\text{CO}_2$ around 30 mm. Hg) both of which lowered the CO_2 content (Fig. 1, point B). After two hours of resuscitative therapy, the buffer base was again virtually normal but the low $p\text{CO}_2$ persisted, with a raised blood $p\text{H}$. This respiratory alkalosis was presumably due to spontaneous overventilation, which was not clinically evident. After sedation, the $p\text{CO}_2$ rose and the $p\text{H}$ fell towards normal.

In a third patient, in whom consciousness did not return after operation (probably after air embolism), coordination over 36 hours between anaesthetist and blood analyses ensured a close control of respiratory function and also of buffer base, such that the patient was given the best chance of recovery.

PROBLEMS OF HYPOTHERMIA

Deliberate cooling of the patient is now common with extracorporeal circulation in surgery of complicated

cardiac defects but hypothermia raises certain fundamental problems which have not been completely solved (Brewin, Gould, Nashat, and Neil, 1955; Symposium, 1959; Neil, 1961; Marshall and Gunning, 1962). Blood gases becoming much more soluble at low temperatures, the oxygen dissociation curve of haemoglobin changes, blood $p\text{H}$ itself alters by about 0.015 per $^{\circ}\text{C}$., the correct calculation of $p\text{CO}_2$ becomes complex (Severinghaus *et al.*, 1956a; Bradley, Stupfel, and Severinghaus, 1956; Severinghaus *et al.*, 1956b) and the use of the standard nomograms, including that of Siggaard-Andersen, would be grossly misleading (Siggaard-Andersen, 1963). Physiologically, the concept of desirable 'normality' for a given temperature is still arguable (Severinghaus, 1959) and some surgeons encourage or induce acidosis during the cold phase (Edmark, 1959; Osborn, Gerbode, Johnston, Ross, Ogata, and Kerth, 1961; Carson and Morris, 1962).

In conclusion, we have found the detailed study of acid-base and other indices to be of much value in the direct clinical management of patients undergoing open-heart surgery, and indeed of other patients with severe metabolic disorders. Further, the team work which this type of study engenders is, we believe, of inestimable value to all concerned.

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