Respiratory Function and Acid-base Status in Accidental Hypothermia Assessed by Arterial Blood Gas Analysis

Michio OKADA and Fumiaki NISHIMURA

To study the respiratory function and acid-base status in hypothermia, we retrospectively reviewed data of arterial blood gas analysis obtained from 63 patients with accidental hypothermia on admission. Twenty-nine showed acidemia and 16 showed alkalemia. The following results were obtained from 57 patients in whom blood gas analysis was performed in room air. PaCO₂ was 46 mmHg or more in 2 and 34 mmHg or less in 46. Most of the patients exhibiting acidemia had metabolic acidosis except 2 with severe pneumonia or subdural hematoma. PaCO₂ was low even in the patients with alkalemia. PaO₂ was 60 mmHg or less in 8, of whom 7 had pneumonia, and 70 mmHg or more in most of the patients without pneumonia. We found that patients with accidental hypothermia generally showed a respiratory function proportionate to their decreased metabolism or hyperventilation, and most of the patients with acidemia exhibited metabolic acidosis.

Key words: Metabolic acidosis, Respiratory acidosis

Accidental hypothermia is not an uncommon condition and is often associated with acidosis and can result in a high mortality (1–7). Although the initial respiratory response to hypothermia is one of stimulation, the respiration begins to become shallow and the rate decreases as the core temperature drops to below approximately 32°C (8). However, in the hypothermic state, metabolism also decreases, and an 8°C drop in body temperature causes a 50% decrease in the production of carbon dioxide (9, 10). Thus, to manage patients with accidental hypothermia, it is important to know whether this reduction in respiratory function is proportional to the decreased rate of metabolism, or not. As it is difficult to assess the effects of hypothermia on the respiratory function in man this issue is still controversial; the changes that occur during induced hypothermia under general anesthesia largely reflect the mechanical ventilation, and in patients with accidental hypothermia, the findings are often complicated by changes produced by coexisting pneumonia, or circulatory failure (1).

In an attempt to clarify the respiratory function and acid-base status in patients with accidental hypothermia, a retrospective study of the arterial blood gas analysis data of patients with accidental hypothermia, including many without pneumonia or circulatory failure, was carried out.

PATIENTS AND METHODS

We reviewed retrospectively the data of arterial blood gas analysis, which had been performed immediately after admission in 63 of the 74 patients with accidental hypothermia who were admitted to Tokyo Metropolitan Charity Hospital. We monitored the core body temperature with a thermometer placed in the rectum, and defined hypothermia as a core body temperature of 34.0°C or lower. The hypothermia occurred by exposure to cold weather as a result of alcohol intoxication or weakness secondary to underlying diseases. Although the duration of exposure to cold weather could not be determined in most of the patients, it was estimated to range from a few hours to a few days. Many of
the patients were alcoholics and/or poorly nourished vagrants. Their mean age was 52 years. Although more detailed clinical data from these 74 patients can be found in a previous study (7), the important data concerning the underlying causes of hypothermia in 63 patients in this study is included here. Thirty-one patients were under the influence of alcohol, 18 had pneumonia or pulmonary tuberculosis, 4 had head injuries, 3 had diabetic ketoacidosis and 2 had drug intoxication.

The arterial blood gas analysis was carried out by percutaneous puncture of the brachial or femoral arteries.

At the time of blood gas analysis, 3 patients had been treated by assisted respiration and 3 patients by oxygen administration. In the remaining 57 patients, the blood gas analysis was performed in room air. PaO₂, PaCO₂ and pH were determined with a blood gas analyzer (M 175, Corning), and corrected for body temperature according to the Kelman and Nunn formula:

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\text{pH}_t = \text{pH}_{37} - 0.015(t - 37) \\
\text{PO}_{2,t} = \text{PO}_{2,e}^{A(37 - t)} \\
\text{PCO}_{2,t} = \text{PCO}_{2,e}^{[0.044(t - 37)]} \\
(A = 0.012 + 0.062 \left[1 - e^{-0.3(100 - \text{O}_2 \text{Sat} \%)}\right],
\]

where pHₜ, PCO₂ₜ, and PO₂ₜ = pH, PCO₂ and PO₂ corrected for body temperature (t), and t = body temperature at which the arterial blood gas analysis was performed. The electrode temperature was maintained at 37°C.

For statistical comparisons, the unpaired t test was employed. p < 0.05 was considered significant.

**RESULTS**

The body temperature of the 63 patients on admission ranged from 24.1°C to 33.8°C (mean, 29.8°C). Pneumonia was observed in 18 patients. Assisted respiration was required immediately after admission before blood gas analysis in 3 patients: this was due to severe pneumonia in one patient, to cessation of breathing following ventricular fibrillation in another, and to ataxic respiration induced by intracranial hemorrhage in the third. No patients required assisted respiration due to impaired respiratory function caused by the hypothermia.

The arterial pH was less than 7.36 in 29 patients and more than 7.44 in 16 (Fig. 1-A). There appeared to be no definite association between pH and body temperature. Of 8 patients in whom the hypothermia appeared to have contributed largely to death, 6 showed acidemia, but none had alkalemia.

We investigated PaCO₂, PaO₂, and the relation between PaCO₂ and pH in 57 patients after excluding the 6 who had been treated by assisted respiration (3 patients) or oxygen administration (3 patients) by the time of blood gas analysis. There was no apparent association between PaCO₂ and body temperature (Fig. 1-B). PaCO₂ was 46 mmHg or more in 2 patients, 34.1–45.9 mmHg in 9, and 34 mmHg or less in 46 patients. One patient with a PaCO₂ of 60.3 mmHg had severe pneumonia, a pH of 7.08 and a PaO₂ of 16.8 mmHg. The same patient was also suffering from drug intoxication. Another patient with a PaCO₂ of 48.3 mmHg was in a deep coma on admission, and died from acute subdural hematoma on the day. There were no records about his respiratory status on admission. Evaluation of the relation between pH and PaCO₂ indicated base deficit in all the patients with
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acidemia (Fig. 2). PaCO₂ was also decreased in most of them. Only the 2 above-mentioned patients exhibited an increase in PaCO₂. Seven patients were within the range of acute base deficit suggesting inadequate compensation for metabolic acidosis by hyperventilation. PaCO₂ and pH in 3 patients with diabetic keto-acidosis was 10.1, 14.9 and 11.6 mmHg, and 6.88, 6.92 and 6.86, respectively. All 3 patients were between acute and chronic base deficit. In all the patients with alkalalemia, PaCO₂ was decreased. About half of them with alkalalemia showed a normal base excess, and the remaining half were in a state of base deficit. None of them exhibited an abnormal base excess. Most of the patients with a normal pH showed a decreased PaCO₂ and base deficit.

Anemia with a hemoglobin value of 10 g/dl or less was observed in 13 patients on admission (Fig. 2). All of these patients revealed a pH of 7.36 or more and were in a state of acute or chronic hypocapnia. In 10 patients with a PaO₂ level of 70 mmHg or less, the extent of decrease in PaO₂ was not associated with the severity of metabolic acidosis (Fig. 2). The base excess was $-17.2 \pm 8.3$ (mean $\pm 1SD$) in 20 patients with a systolic blood pressure of 80 mmHg or less and $-7.86 \pm 6.8$ (mean $\pm 1SD$) in 37 patients with that of more than 80 mmHg; more severe metabolic acidosis was

![Diagram of Acid-base balance in 57 patients with accidental hypothermia](image)

**Fig. 2.** Acid-base balance in 57 patients with accidental hypothermia. Closed symbols = Twenty patients with a systolic blood pressure of 80 mmHg or less, Boxes = Thirteen patients who had anemia with a hemoglobin value of 10 g/dl or less, * = Ten patients with a PaO₂ level of 70 mmHg or less.
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observed in the patients with a lower blood pressure (p < 0.001) (Fig. 2).

No definite association was found between PaO₂ and body temperature (Fig. 3). Of 8 patients with a PaO₂ of 60 mmHg or less in room air, 7 had pneumonia. Of the 6 patients who had been treated by assisted respiration or oxygen administration before blood gas analysis, 2 with pneumonia showed a PaO₂ of 60 mmHg or less. PaO₂ was 70 mmHg or more in all patients without pneumonia except 2, and 100 mmHg or more in 22 patients. Of these 22 patients, 21 revealed a PaCO₂ value of 30 mmHg or less. Without correction for body temperature, PaO₂ was 150 mmHg or more in many patients with a body temperature of about 25°C and 100 mmHg or more in 8 patients with pneumonia, demonstrating the danger of underestimating the severity of hypoxemia.

The rate and depth of respiration were unclear in most of the cases due to inaccurate records on admission. There was one patient with a body temperature of 25°C who apparently stopped breathing and was sent to the hospital for confirmation of death. The PaCO₂ was 22.7 mmHg, PaO₂ was 23.5 mmHg and pH was 7.4 in this patient. He died from severe pneumonia.

**DISCUSSION**

This study presents arterial blood gas analysis data obtained from 63 patients with accidental hypothermia. The blood gas analysis was performed on admission in all patients and without assisted respiration or oxygen treatment in most of them. Pneumonia was observed in 18 patients but not in the remaining 45. This study may thus facilitate the clarification of the respiratory function and acid-base balance in patients with accidental hypothermia in a state which was not influenced by respiratory complications.

PaCO₂ was markedly increased in only one patient with severe pneumonia and drug intoxication, but was decreased in most of the patients. These findings suggest that the ventilation required for decreased metabolism is maintained at a body temperature of about 25°C or above when severe pneumonia or other factors inhibiting respiration are absent. In accidental hypothermia, metabolic acidosis or hypoxemia induced by pneumonia frequently develops. To compensate for these conditions, hyperventilation is considered to occur, resulting in a decrease in PaCO₂. However, PaCO₂ was also decreased in patients without metabolic acidosis or pneumonia. In addition, PaCO₂ decreased to 30 mmHg or less in most of the patients showing a PaO₂ value of 100 mmHg or more and in all the patients with alkalemia. These findings suggest that in patients with hypothermia of about 25°C or above without complications, ventilation is generally proportionate to decreased metabolism. Interestingly, these responses resemble those observed in turtles, hamsters, and squirrels in a hypothermic state (1). However, 7 patients showed a base deficit with an inadequate decrease in PaCO₂ (area of acute base deficit) suggesting a decreased respiratory function reserve that could not increase ventilation sufficiently to completely compensate for metabolic acidosis. Such a condition should also be considered in the management of hypothermic patients, although it is infrequent.

A general concept of hydrogen ion regulation which would account for the acid-base regulation in most animals, ranging from simpler forms in the sea to homeotherms and man, is based on the pre-
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Preservation of neutrality of the intracellular state at the particular organism’s body temperature. This preservation of neutrality is believed to be dependent upon the dissociation of water and is regulated by the compliant protein buffer, imidazole of histidine, which exists in sufficient concentration in our blood, and of which the dissociation constant (pK) is close to 7. The extracellular environment, as a reservoir for acid metabolites of the tissue, is maintained at a constant alkalinity relative to neutrality through the interaction of a multibuffer system that not only requires the unique properties of the protein buffer imidazole of histidine, but also the precise regulation of the bicarbonate buffer ratio by proper ventilation and renal control. Based on this system, $\Delta \text{pH}/\text{°C}$ of $-0.0147$ exhibited by in vitro blood of constant CO$_2$ content is very similar to the temperature-dependent pH of neutral H$_2$O, i.e., $\Delta \text{pH}/\text{°C} = -0.017$, and neutrality of the intracellular state and a constant relative alkalinity of the circulating blood can be maintained at any body temperature (12). Therefore the ideal pH of arterial blood at 25°C is considered to be 7.58 ($7.4 + 0.0147 \times 12$) on the basis of this concept.

The reported respiration rate in patients with hypothermia varies from several/min to tachypnea (2, 3). The rate and depth of respiration in our patients were of interest but remained unclear due to inaccurate admission records. However the present patients include one patient with a body temperature of 25°C who apparently stopped breathing and was sent to the hospital for confirmation of death. His PaCO$_2$ was 22.7 mmHg. Therefore, at a body temperature of about 25°C, shallow respiration that may be mistaken for cessation of breathing would seem to be sufficient in the decreased metabolic state.

Many patients with hypothermia who developed respiratory acidosis due to hypoventilation have been reported (1). However, most of such patients had severe pneumonia. The contribution of pneumonia to acidosis might thus have been greater than that of hypothermia in these reported patients. Although only a few patients developed respiratory acidosis in the present study, this condition should be considered in the management of patients with accidental hypothermia because pneumonia is frequently complicated in accidental hypothermia.

In accidental hypothermia, PaO$_2$ has been reported to decrease due to a severe reduction in pulmonary ventilation or reduction in alveolo-capillary oxygen transfer. Many of the reported patients with accidental hypothermia revealed a PaO$_2$ level of 70 mmHg or less (1, 4). However, in the present study, a marked reduction in PaO$_2$ was not frequently observed in patients without pneumonia; rather, PaO$_2$ was increased in many of the patients, which is inconsistent with other reports. However, most of these reported patients with decreased PaO$_2$ had pneumonia. In addition, some patients without pneumonia who showed a PaO$_2$ level of 100 mmHg or more have also been described (5). These findings suggest that the inconsistency of our results with those of earlier reports reflects the differences in the subjects studied. In uncomplicated hypothermia of 25°C or above, PaO$_2$ generally does not appear to decrease. Therefore, in patients with accidental hypothermia exhibiting a decreased PaO$_2$, complications such as pneumonia should be strongly suspected.

A greater amount of O$_2$ or CO$_2$ can be dissolved in the blood at the same PaO$_2$ or PaCO$_2$ at a low temperature than at 37°C. Blood gas analysis in hypothermic patients carried out using electrodes operating at 37°C produces higher values unless the data are corrected for the body temperature at the time of blood collection. Blood gas analysis in patients even with pneumonia also frequently reveals a PaO$_2$ value of 100 mmHg or more unless the data are corrected for the body temperature. It is important not to be misled by such values. There is considerable controversy on whether arterial blood gases should be temperature corrected and many recent reports state that correction is unnecessary and possibly misleading (13). However, the present data showed that it is better to correct the arterial blood gases for body temperature, at least PaO$_2$ and PaCO$_2$ in the clinical setting.

Metabolic acidosis has been reported to result from lactic acidosis produced by anaerobic metabolism due to tissue hypoxia (14), a reduction of hepatic metabolism of lactic, pyruvic and other organic acids, or an impaired acid excretory capacity of the kidney (15, 16). Tissue hypoxia has been reported to result from arterial hypoxemia, a leftward shift of the oxyhemoglobin dissociation curve,
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decreased cardiac output, or increased peripheral resistance caused by enhanced blood viscosity (16). The data from the present study do not identify a definite cause of metabolic acidosis but allow the following speculations to be made. Arterial hypoxemia is not a major causative factor, but decreased blood pressure is one of the contributing factors. Patients with a low hemoglobin value are not likely to develop metabolic acidosis. Since decreased tissue perfusion in hypothermia has been reported to be strongly associated with increased blood viscosity (1, 17), decreased hemoglobin appears to prevent the development of metabolic acidosis by reducing the increase in blood viscosity in hypothermia.

There are several limitations in this study. First, because this was a retrospective study, the clinical information was not complete in all cases. However, several laboratory tests including blood gas analysis were performed in most cases. Therefore despite the limitation of being a retrospective study, this study provides the most detailed clinical data among the clinical studies of accidental hypothermia and important information concerning respiratory function and acid-base status in accidental hypothermia. Secondly, in contrast to basic physiological and experimental studies, common commercially-available equipment for blood gas analysis was used, and rectal temperature rather than blood temperature was measured. This difference in temperature certainly affects the results. In order to estimate respiratory function in the hypothermic state, it is probably necessary to measure the temperature of pulmonary capillary blood. As it is impossible to measure pulmonary capillary blood temperature, and rectal temperature is probably closer to the pulmonary capillary temperature than the temperature of arterial blood obtained from the arm or leg, it is reasonable to correct the results of blood gas analysis for rectal temperature instead of for the temperature of the arterial blood sample obtained. However, the fact that PaO₂ was often higher than 100 mmHg could be explained by this difference in temperature, so that the temperature of pulmonary capillary blood might have been lower than the rectal temperature and the results might have to be corrected for an even lower temperature in such cases. Thirdly, many patients had severe underlying diseases other than pneumonia. These underlying diseases might affect the results. The effect of some of these underlying diseases has been discussed in an earlier paper (7).

In conclusion, the present study revealed that most of the patients with accidental hypothermia showed a respiratory function proportionate to their decreased metabolism or hyperventilation at a body temperature of about 25°C or above.

REFERENCES