THE CONTROL OF VENTILATION IN HYPOXIA II - CLINICAL IMPLICATIONS

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In the first of these two articles (1) it was pointed out that increased ventilation and a lowered alveolar PCO_2 accompany acclimatization to high altitude, as was well established prior to 1950 (2,3,4,5,6,7,8).

The lowering of arterial PCO_2 in chronic hypoxia can be formally related to the arterial PO_2 (PaO_2), redefining normal PCO_2 according to the existing arterial oxygen tension. It is hoped that this article will demonstrate the value of knowing what the arterial PCO_2 should be for a given degree of hypoxia (aided by the use of a diagram). This is important because it enables us to assess whether a subject's respiratory control has made the normal chronic hypoxic adjustment to breathing. In the first article a formula was given to calculate the arterial PCO_2 we expect for a given chronic hypoxic arterial oxygen tension (PaO2) with high altitude acclimatization (1,9):

Expected $PaCO_2$ = actual PaO_2 times 0.25 plus 15 or 2 (mm Hg or kPa).

Recent confirmation that $PaCO_2$ at altitude depends on PaO_2

After altitude acclimatization in healthy normal subjects, at Everest Base Camp on the British Mount Everest Medical Expedition in 1994, mean arterial PCO_2 was 27.0 mm Hg (3.6 kPa), much as predicted (25.9 mm Hg, 3.45 kPa) from the mean measured arterial PO_2 of 43.6 mm Hg (5.81 kPa) (10). We can simplify assessment if we use the chart presented in figure 1, where the bold line represents the equation. We can see at a glance that 27.0 mm Hg (3.6 kPa) is close to the expected $PaCO_2$ value.

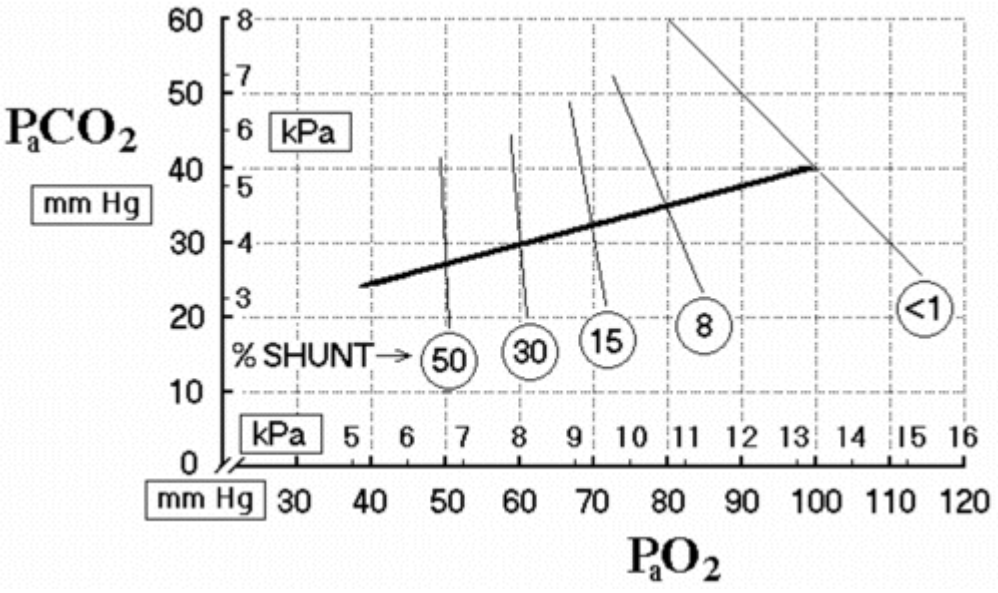

Figure 1. This diagram, with arterial PCO_2 and PO_2 ($PaCO_2$ and PaO_2) as the axes, shows the adjustment of $PaCO_2$ which is made by air breathing normal subjects in chronic hypoxia at altitude as the bold diagonal line. $PaCO_2$ and PaO_2 of patients at sea level with chronic stable hypoxia and normal respiratory control also fall on this line (equation: Normal, or expected, $PaCO_2 = 0.25\ PaO_2 + 15$ mm Hg, or + 2 kPa) which therefore acts as a reference "normal" $PaCO_2$ appropriate to the degree of chronic hypoxia.
The approximate % shunt (equivalent pure shunt) is indicated for selected normal values, by means of 'iso-shunt' lines extending upward, ending at $PaCO_2$ values 1.5 times the normal, and downward to $PaCO_2$ values which are 2/3 normal. The high end represents hypoventilation (alveolar ventilation 67% of normal), the lower end hyperventilation (alveolar ventilation 150% of normal). [Sometimes called the 'Chinese Junk diagram'.]

Clinical and physiological implications at sea level - the normal value of PCO2

The bold line in the figure is not only representative of normal control in the hypoxia of high altitude but also applies at sea level to hypoxic patients with normal respiratory control (e.g. chronic stable asthma; (11,1)). A $PaCO_2$ of 40 mm Hg (5.3 kPa) is normal where PaO_2 is normal (100 mm Hg, 13.3 kPa) . Similarly, for assessment of hypoxic patients, for example with a PaO_2 50 mm Hg (6.7 kPa) , a $PaCO_2$ of 27.5 mm Hg (3.7 kPa) would be normal.

Assessment of hypo- and hyper- ventilation is simplified by the chart (figure 1). Where a patient's $PaCO_2$ is well above the bold line he/she is hypo-ventilating. This means that hypoxic patients with COAD and a $PaCO_2$ of 40 mm Hg (5.3 kPa) are hypo-ventilating, because the line predicts lower normal $PaCO_2$s in hypoxia; for a PaO_2 of 60 mm Hg (8 kPa) the line (and equation) predict a normal $PaCO_2$ of 30 mm Hg (4 kPa). Alveolar ventilation here is 75% of normal (100 times the predicted $PaCO_2$ divided by the measured value, i.e. 100 x 30/40 in this example). Taking PaO_2 into consideration should also give earlier (and more realistic) warning of hypoventilation in patients with status asthmaticus (12).

Hyper-ventilation exists when the patient's $PaCO_2$ is below the line. There is a need to revise assessment of patients with chronic stable asthma, many of whom are mildly hypoxic (11) with lower $PaCO_2$s than normal subjects. They are usually assumed to be hyperventilating, but their $PaCO_2$ values, according to the present approach, are normal because they are appropriate to their lowered PaO_2. We will next examine the use of the thin lines on the chart (fig. 1) but first point out that alveolar ventilation at either end of them is: normal x 1.5 (lower end) or normal / 1.5 (upper end).

In hypoxic patients at sea level with lung disease blood flow through parts of the lung, in effect, bypasses gas exchange. This bypass is referred to as shunt effect. Lines on the chart show percent shunt (calculated from the 'shunt equation'). This is the theoretical percentage of total lung blood flow completely bypassing gas exchange (%shunt) which would give the blood gas values. The real situation involves more lung, but with poor gas exchange rather than none. Changes in ventilation will move blood gas values for a given %shunt up or down that ('iso-shunt') line (13).

The %shunt is crudely equivalent to the amount of non-functioning lung. For a normal subject it is less than 1% (fig 1). For a patient with an arterial PO_2 of 50 mm Hg (6.7 kPa) shunt effect is about 50%. A limited number of iso-shunt lines are given on the chart to help in quantitative assessment of lung function as PaO_2 changes.

Clinical and measurement implications for moderate hypoxia at high altitude

Measurement of the precise blood gas values with a variety of ascent profiles, would improve our description of the adjustments made by normal subjects in the real context of high altitude activity. It is likely that concurrent assessment by means of AMS scores would result in important criteria for judging when to recommend slowed ascent. Resting alveolar (end-tidal) PCO_2 could be substituted for arterial values. Low PO_2 values at altitude occur with normal lungs (minimal shunt effect) so a different model for assessment of shunt is applicable at altitude from that applicable at sea level. The thin lines in figure 1 are therefore not applicable to altitude. Further calculations (from barometric pressure and blood gasses) are needed to give %shunt at altitude but, once available, should help in early detection of high altitude pulmonary oedema (edema, HAPE).

The 'normal' (bold) line (fig 1) is the same at altitude as at sea level so adequacy of alveolar ventilation is assessable from the existing chart. It is recommended that efforts be directed toward more extensive measurement of alveolar or arterial PCO_2 and arterial PO_2 (and barometric pressure) at high altitude.

In Summary

This article shows how the adequacy of resting ventilation can be assessed by use of the chart of $PaCO_2$ against PaO_2 illustrated in figure 1 using the bold line, both at altitude and at sea level. At sea level the degree of lung functional impairment (%shunt) can also be read off. Further work is needed for %shunt to be available at altitude. It is suggested that significant improvement in diagnosis and management of high altitude sickness will be achieved by undertaking more, ongoing, high altitude arterial blood gas measurement (as well as barometric pressure) in parallel with clinical assessment. This means concentrating on improvements in blood gas apparatus to make this practical.

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