Zander, Mertzlufft (eds.): The Oxygen Status of Arterial Blood.
pp. 203–208 (Karger, Basel 1991)

Calculation of O_2 Concentration

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Introduction

The O_2 concentration of the blood includes the greater proportion of oxygen chemically bound to hemoglobin, as well as a smaller amount of physically dissolved oxygen. Whereas the chemically bound O_2 is only found in the erythrocytes, the physically dissolved O_2 is distributed between erythrocytes and plasma.

In the event that the O_2 concentration (O_2 content) of arterial blood must be known but the appropriate measurement technique is not available, an attempt can be made to estimate the O_2 concentration from other available data. For calculating the amount of chemically bound O_2 the Hb concentration (cHb, g/dl) and the O_2 saturation (sO_2, %) are required; for the physically dissolved O_2 concentration, the O_2 partial pressure (pO_2, mmHg) and O_2 solubility (αO_2, ml/ml/atm) are necessary. If these data are not all available, the O_2 concentration can only be determined approximately. This is illustrated in the two examples given below.

Modern multi-wavelength oxymeters (CO- or Hem-oxymeters) with 4–7 wavelengths are able to calculate the amount of chemically bound O_2 from the cHb and sO_2; this value, however, neglects the amount of physically dissolved oxygen. This would lead in the case of hyperoxia, for example, to a calculated O_2 concentration that would lie significantly below the true cO_2.

Blood gas analyzers, some of which are able to measure the Hb concentration, calculate the O_2 saturation from data on the acid-base

status and the measured pO_2, and thus, on the basis of the cHb, the amount of chemically bound O_2 is derived. From a given value for the O_2 solubility and the measured pO_2, the amount of physically dissolved O_2 can be estimated, and thus the O_2 concentration can be calculated.

However, this procedure can also only yield an approximate value for the O_2 concentration since several simplifying assumptions must be made (normal O_2 binding curve, O_2 solubility) and only the so-called partial O_2 saturation (psO_2, %) can be used. This last point (psO_2) is considered elsewhere in this book (e.g. in the Appendix).

The data necessary for calculating the exact O_2 concentration of blood will be described here, together with the calculation procedure.

Chemically Bound Oxygen

Since 1 mol of Hb can bind a maximum of 4 mol O_2, a value is obtained for the so-called theoretical Hüfner number of 1.39 ml O_2/g Hb, assuming a molecular weight for the Hb molecule of 64,458 and a molar volume for oxygen of 22.394 l/mol. These data are always associated with the name Hüfner, since in 1894 he made the first experimental attempts to confirm them [3]. However, neither Hüfner nor several other authors have succeeded in measuring these parameters. All values measured later have lain between Hüfner's value of 1.34 ml/g and the theoretical value of 1.39 ml/g.

The reasons for this are, on the one hand, that traces of COHb, MetHb and SulfHb cannot be completely eliminated experimentally and, on the other hand, that difficulties have been encountered in the necessary correction of the physically dissolved oxygen. It is therefore recommended that only the theoretical Hüfner number of 1.39 ml/g should be used and that possible traces of COHb, MetHb and SulfHb, which can lead to a decrease in O_2 concentration, be taken into account in assessing the O_2 saturation of the blood. This recommendation has already become normal practice in most modern oxymeters and blood gas analyzers.

The above considerations indicate how the amount of chemically bound oxygen should be calculated. When the Hb concentration (cHb) and the O_2 saturation (sO_2) are known, the O_2 concentration is obtained as follows:

$$cO_2\,(ml/dl) = cHb\,(g/dl) \times sO_2 \times 1.39\,(ml/g)$$

It should be noted that the true sO_2 (not the partial) must be used and that the saturation is expressed as a fraction rather than as a percentage (e.g. $sO_2 = 50\%$ is expressed as 0.5).

At an Hb concentration of 15 g/dl and an O_2 saturation of 97%, for example, a value for the concentration of chemically bound O_2 alone of 20.2 ml/dl is obtained.

Physically Dissolved Oxygen

According to Henry's law, the concentration of physically dissolved O_2 is given by the product of the O_2 partial pressure and the O_2 solubility coefficient, αO_2. The latter is usually expressed as the so-called Bunsen solubility coefficient, i.e. ml O_2/ml liquid/atmosphere partial pressure (ml/ml/atm), and is dependent upon temperature.

Although a large number of O_2 solubility coefficients are known for different liquids, also at 37°, determination of the solubility of O_2 in the blood presents a particular difficulty. The comparatively small concentration of physically dissolved O_2 must be determined in the presence of a very high concentration of chemically bound O_2. With one exception [2], a procedure has always been used in which the hemoglobin is oxidized, with formation of MetHb, so that a reversible binding of O_2 is prevented.

A different procedure has been used with the aim of determining the solubility of O_2 in human blood at 37° under largely physiological conditions [6]. On the one hand, the O_2 concentration was measured in blood samples whose pO_2 values were between 170 and 700 mmHg, i.e., the hemoglobin was always saturated with O_2 and the increased O_2 concentration with increasing pO_2 therefore represented the O_2 solubility. On the other hand, the O_2 concentration was determined in blood samples that had been equilibrated with 30% CO in order to prevent O_2 binding to hemoglobin.

The results of these investigations are summarized in figure 1 and can be outlined as follows: (1) Starting from the O_2 solubility of plasma previously determined [5], the O_2 solubility of blood increased with increasing Hb concentration; (2) the results did not differ between the two methods (exclusion of the influence of Hb by either high pO_2 values or with CO); (3) erythrocyte membranes also had no effect on the O_2 solubility. It is apparent that the values reported here for the O_2 solubility lie clearly

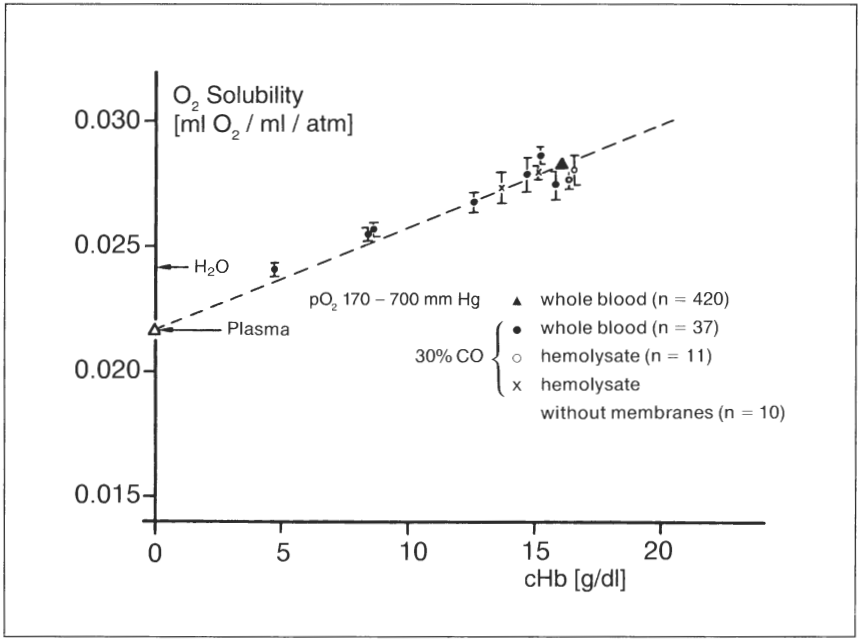

Fig. 1. Measured values for the O_2 solubility of blood in ml/ml/atm at 37°C as a function of the Hb concentration (cHb) expressed in g/dl (data taken from [6]). Starting from the O_2 solubility of plasma, the O_2 solubility of blood increases linearly with increasing Hb concentration. Erythrocyte membranes have no effect on the O_2 solubility. The experimental procedure for eliminating O_2 binding to Hb (pO_2 170–700 mmHg or inhibition with 30% CO) apparently does not influence the measured values.

above the most cited values from Van Slyke's group [4] (0.0237 ml/ml/atm for normal blood at 37°C).

If the Hb concentration (g/dl) or hematocrit (vol.%) are known, the O_2 solubility of the blood in ml/ml/atm can be obtained using the measured O_2 solubility of plasma (0.0217 ml/ml/atm) [5] as follows:

$\alpha O_2 = cHb \times 0.00041 + 0.0217$ or
$\alpha O_2 = Hct \times 0.000137 + 0.0217.$

An Hb concentration of 15 g/dl (Hct = 45%) would thus give an O_2 solubility coefficient of 0.0279 ml/ml/atm.

For practical reasons the O_2 solubility coefficient can be given as

ml/dl/mmHg (instead of ml/ml/atm), from which the following values are obtained:

0.0037 ml/dl/mmHg at cHb = 15 g/dl,
0.0034 ml/dl/mmHg at cHb = 10 g/dl,
0.0031 ml/dl/mmHg at cHb = 5 g/dl,
0.0029 ml/dl/mmHg for plasma.

Calculation of the concentration of physically dissolved O_2 can now be performed from the product of pO_2 and αO_2 if the O_2 partial pressure (pO_2, mm Hg) is known:

$$cO_2\,(ml/dl) = pO_2\,(mm\ Hg) \times \alpha O_2\,(ml/dl/mm\ Hg).$$

At a pO_2 of 90 mmHg and an αO_2 of 0.0037 ml/dl/mmHg (i.e. normal blood), a concentration of physically dissolved O_2 of 0.33 ml/dl would thus be obtained; at a pO_2 of 600 mmHg (hyperoxia) this value would be 2.2 ml/dl.

Calculation of O_2 Concentration

Since the O_2 concentration (cO_2; ml/dl) is obtained from the sum of the chemically bound and physically dissolved O_2 concentrations, the relationship is as follows:

$$cO_2\,(ml/dl) = (cHb \times sO_2 \times 1.39) + (pO_2 \times \alpha O_2),$$

where cHb is expressed in g/dl, sO_2 is expressed as a fraction, pO_2 is expressed in mm Hg and αO_2 in ml/dl/mmHg. In normal blood, for example, with cHb = 15 g/dl, sO_2 = 97% and pO_2 = 90 mmHg, this amounts to an O_2 concentration of 20.6 ml/dl.

For practical purposes it is recommended that the physically dissolved O_2 is taken to be constant at 0.3 ml/dl, as long as the pO_2 lies between 60 and 100 mmHg and the Hb concentration is between 10 and 20 g/dl. Under these conditions the physically dissolved O_2, and therefore the O_2 concentration of the blood, varies maximally by ± 0.1 ml/dl, i.e., always less than ± 1% of the O_2 concentration in the blood.

Summary

For calculating the O_2 concentration of blood, knowledge is required of the Hb concentration (cHb, g/dl), the O_2 saturation (sO_2, %), the theoretical Hüfner number of 1.39 ml/g, the partial pressure (pO_2, mmHg), and the O_2 solubility (αO_2 ml/dl/mmHg). New data on the O_2 solubility in human blood allow the precise calculation of the O_2 concentration especially in the case of hyperoxia.

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