Theory of Hyperbaric Oxygenation

Nomogram for Oxygen Content, Saturation and Pressure at Hyperbaric Conditions

Robert L. Fuson, M.D., Herbert A. Saltzman, M.D.,† C. Frank Starmer, M.S.E.E.,‡ Wirt W. Smith, M.D.§*

A graph is presented which describes the relations in blood for oxygen content, oxygen tension and oxygen saturation at various concentrations of hemoglobin. This chart permits the rapid, direct readout of oxygen content of blood from either oxygen tension or of hemoglobin. Oxygen tension and saturation of hemoglobin can also be plotted directly from the oxygen content of blood.

THE HYPERBARIC oxygenation therapist requires a more facile means of calculating oxygen transport in blood than is generally available. While clinical interest in hybaroxia, or hyperbaric oxygenation, is recent, the actual principles by which oxygen transport is calculated are identical to those enumerated in the classic studies of hemoglobin-oxygen dissociation.[1, 2] In order to facilitate the measurement of the relations in blood between oxygen tension, saturation of hemoglobin, and oxygen content at various concentrations of hemoglobin, a graph has been constructed based on previously described formulas, constants, and empirical data.

Methods

The oxygen content (C) of whole blood is the sum of two fractions, *i.e.*, that bound to hemoglobin (C_H) and that in physical solution (C_p):

$$C = C_H + C_p \quad (1)$$

The volume of oxygen bound to hemoglobin (C_H) equals the product of the hemoglobin concentration (Hb) in grams per 100 ml. of whole blood times the hemoglobin oxygen carrying factor of 1.34 ml. of oxygen per gram of saturated hemoglobin times the percentage of hemoglobin oxygen saturation (% Sat.).[2] In all instances hemoglobin oxygen saturation is based on the specific oxygenation of reduced hemoglobin rather than the total oxygen content of blood as related to hemoglobin concentration. For this reason the saturation of hemoglobin cannot exceed 100 per cent and is so expressed.

$$C_H = Hb \times 1.34 \times \frac{\%\ Sat.}{100} \quad (2)$$

The volume of oxygen in physical solution (C_P) is equal to the product of the oxygen tension (Po_2) times the solubility factor of 0.0031 * ml. oxygen per 100 ml. of blood per millimeter of mercury oxygen tension:

$$C_P = Po_2 \times 0.0031 \quad (3)$$

Equation 1 may now be rewritten as follows:

$$Hb \times 1.34 \times \frac{\%\ Sat.}{100} + Po_2 \times 0.0031 = C\ (\text{Total blood oxygen content in vols. } \%) \quad (4)$$

The relationship of hemoglobin oxygen saturation to oxygen tension in blood is defined by the hemoglobin-oxygen dissociation curve.[1, 3]

* Derived from the Bunsen coefficient.[7]

* U.S.P.H.S. Post-Doctoral Fellow in Hyperbaric Surgery.
† Associate Professor of Medicine.
‡ Research Associate, Department of Medicine.
§ Associate Professor of Experimental Surgery, Duke University Medical Center, Durham, North Carolina.

Received from the Departments of Surgery, Medicine and Engineering, Duke University Medical Center; accepted for publication August 3, 1965. Supported in part by U.S.P.H.S. Research Grants HE 07896, HE 07563 and HE 04702.

[4, 5] Moreover, Severinghaus has plotted the hemoglobin-oxygen dissociation curve in tabular form with appropriate correction factors for temperature and *p*H [6] (fig. 1). The graph presented in this communication has been constructed on the basis of equation 4 and the relationship of hemoglobin oxygen saturation to oxygen tension in blood at 37° C. and *p*H 7.4. The coordinate scales have been so chosen to produce a family of curves which are as nearly linear as practical in describing these relationships.

Discussion

This graph permits the direct, convenient readout of oxygen tension, hemoglobin oxygen saturation, and oxygen content in blood at varoius hemoglobin concentrations. This chart should be particularly useful where oxygen tension in blood is the primary measurement as is commonly the case with polarographic techniques. Knowing the hemoglobin concentration, the family of curves (fig. 2) permits the following quick computations: (1) conversion of oxygen tension to oxygen content, (2) conversion of hemoglobin oxygen saturation to oxygen content, and (3) conversion of oxygen content to oxygen tension and the corresponding hemoglobin oxygen saturation. Examples:

(1) Given: Oxygen tension = 45 mm. of mercury, Hb concentration = 11 g. per 100 ml.. Find: Oxygen content of blood. Enter the graph horizontally from the blood oxygen tension of 45 mm. Hg on the right and proceed to the left until this line intersects the hemoglobin concentration diagonal of 11 g. per 100 ml. From this intersection drop vertically to a blood oxygen content of 12 volumes per cent.

(2) Given: Hemoglobin oxygen saturation = 70 per cent, Hb concentration = 17 g. per 100 ml. Find: Oxygen content of blood. Enter the chart horizontally from the hemoglobin oxygen saturation of 70 per cent on the left and proceed to the right until this line intersects the hemoglobin concentration of 17 g. per 100 ml. From this intersection, drop vertically to an oxygen content in blood of 16 volumes per cent.

(3) Given: Oxygen content = 24 volumes per cent, Hb concentration = 12 g. per 100 ml. Find: Percentage of hemoglobin oxygen saturation and oxygen tension in blood. Enter the graph vertically from the oxygen content of 24 volumes per cent and proceed upward until this line intersects the hemoglobin concentration diagonal of 12 g. per 100 ml. Proceed horizontally from this intersection to a hemoglobin oxygen saturation of 100 per cent on the left and an oxygen tension in blood of 2,500 mm. of mercury on the right.

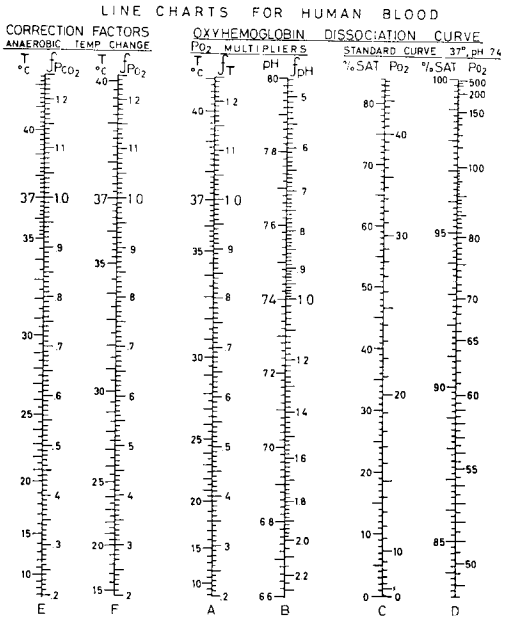

FIG. 1. This nomogram permits the rapid determination of relations between P_{O_2} and oxygen saturation in human blood within a large range of both *p*H and temperature.[6] The P_{O_2} measured at 37° C. is divided by the correction factor for *p*H, measured under the same conditions. The saturation of hemoglobin can be read directly from the nomogram opposite this computed value.

These examples are valid for standard conditions of temperature (37° C.) and *p*H (7.4). In those situations requiring correction for temperature and *p*H, the conversion factors of Severinghaus may be employed.[6] When the temperature is below 37° C. or the *p*H is above 7.4, the oxygen content obtained from this graph will be slightly less than the true value. Conversely, when the temperature is above 37° C. or the *p*H is below 7.4, the oxygen content as read from the chart will be slightly higher than the true value. However, within a temperature range of 35° to 37° C. or within a *p*H range of 7.3 to 7.5, the actual error in oxygen content as derived from a measured P_{O_2} or percentage saturation in blood will be less than 0.1 volumes per cent and therefore not be of clinical significance.

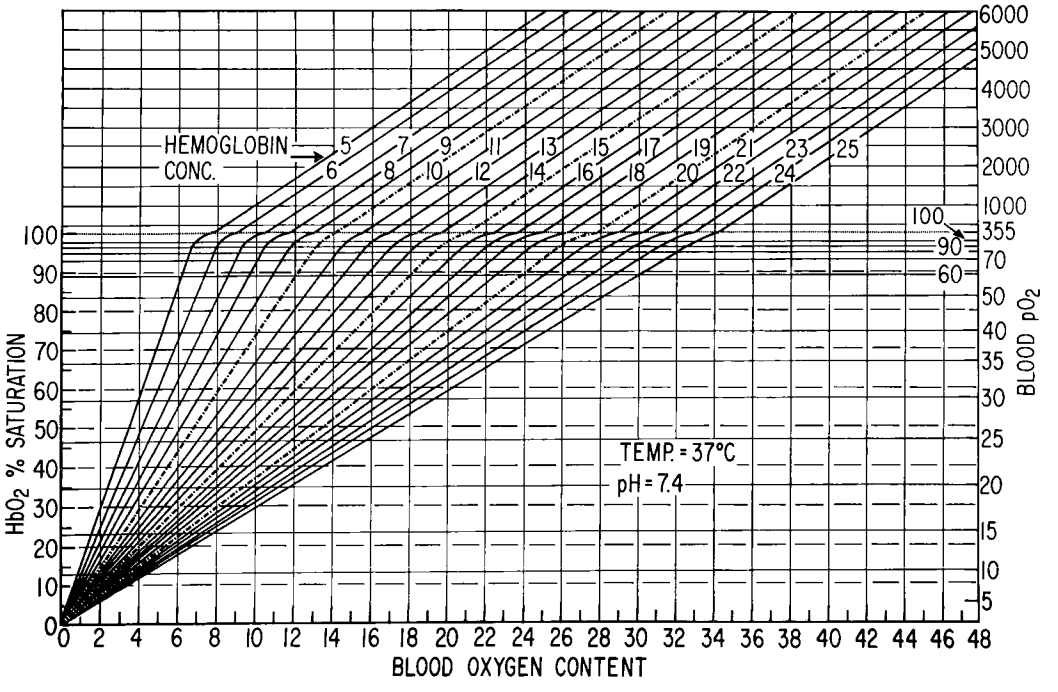

FIG. 2. Hemoglobin oxygen saturation is displayed on the left vertical axis; blood oxygen tension from 0 to 6,000 mm. of mercury is given on the right. The lower horizontal axis depicts blood oxygen content in volumes per cent from 0 to 48. Various hemoglobin concentrations are plotted diagonally across the graph.

However, unless appropriate correction is made for these variations in temperature and *p*H, the reading error for oxygen tension of blood as derived from measured oxygen content approaches 10 per cent for similar deviations. Furthermore, the asymptotic character of the hemoglobin dissociation curve for oxygen between 90 and 100 per cent saturation causes crowding of the Po_2 scale on the graph. As a result the accurate readout of Po_2 becomes most practical above 355 and below 60 mm. of mercury.

The oxygen solubility factor of 0.0031 for blood is based on a hemoglobin concentration of 15 g. per 100 ml. When the hemoglobin concentration exceeds 15 g. per 100 ml., the actual amount of dissolved oxygen will be slightly higher than indicated on the chart. Similarly, when the hemoglobin concentration is below 15 g. per 100 ml., the actual amount of dissolved oxygen will be slightly lower than read. This is due to the greater solubility of oxygen in red cells than in an equal volume of plasma (solubility factor for red cells = 0.0035 * ml. of oxygen per 100 ml. of red cells per millimeter of mercury oxygen tension). Again, the reading error for oxygen content caused by variations in hemoglobin concentration is very small and is not clinically significant.

This graph also allows the rapid clinical assessment of the relationships between various oxygen transport factors in blood during hyperbaric oxygenation. For example, with a hemoglobin concentration of 8 g. per 100 ml., and an oxygen tension of 100 mm. of mercury, the oxygen content of blood is 11 volumes per cent. If the Po_2 is raised to 3,000 mm. of mercury by hyperbaric oxygenation, the oxygen content of the same blood is 20 volumes per cent. However, if the oxygen tension is held constant at 100 mm. of mercury and the hemoglobin concentration is raised by transfusion to 15 g. per 100 ml., the oxygen content of blood would also be 20 volumes per cent.

Summary

A graph is presented which describes the relations among oxygen content, oxygen tension and hemoglobin oxygen saturation in blood at various hemoglobin concentrations. This chart permits the rapid determination of these relations without extensive calculations.

References

1. Forbes, W. H., and Roughton, F. J. W.: The equilibrium between oxygen and hemoglobin. I. The oxygen dissociation curve of dilute blood solutions, J. Physiol. 71: 229, 1931.
2. Van Slyke, D. D., and Neill, M. M.: The determination of gases in blood and other solutions by vacuum extraction and manometric measurement. VII. The determination of oxygen in blood, J. Biol. Chem. 61: 554, 1924.
3. Dill, D. B., and Forbes, W. H.: Respiratory and metabolic effects of hypothermia, Amer. J. Physiol. 132: 685, 1941.
4. Paul, W., and Roughton, F. J. W.: The equilibrium between oxygen and hemoglobin at very low percentage saturations, J. Physiol. 113: 23, 1951.
5. Nahas, G. G., Morgan, E. H., and Wood, E. H.: Oxygen dissociation curve of arterial blood in man breathing high concentrations of oxygen, J. Appl. Physiol. 5: 169, 1952.
6. Severinghaus, J. W.: Oxyhemoglobin dissociation curve correction for temperature and *p*H variation in human blood, J. Appl. Physiol. 12: 485, 1958.
7. Sendroy, J., Jr., Dillon, R. T., and Van Slyke, D. D.: Studies of gas and electrolyte equilibria in blood. XIX. The solubility and physical state of uncombined oxygen in blood, J. Biol. Chem. 105: 597, 1934.

MANNITOL Ten per cent mannitol infusions were given to dogs before, during, and after graded hemorrhage. Mannitol infusion regularly produced an increase in renal blood flow, but only as a reflection of increase in cardiac output. When a shift in flow distribution occurred with hemorrhage alone, blood flow was preferentially shifted toward the kidney. When a relative shift in flow distribution occurred after mannitol infusion, it was always away from the kidney. (*Schenk, W. G., and others: Effect of Mannitol Infusion on Cardiac Output and Renal Blood Flow After Graded Hemorrhage, J. Thor. Cardiov. Surg. 50: 561 (Oct.) 1965.*)

VASOPRESSORS The effects of drugs on the heart were studied. Systemic perfusion and cardiac work were maintained constant by using a pump and fluid reservoirs, and keeping the heart empty. Each animal was his own control and received 15 minute infusions of the drugs. Doses, in micrograms per kilograms per minute were: isoproterenol 1.5 to 2.5, levarterenol 1.5 to 2.5, epinephrine 1.5 to 2.5, metaraminol 10, phenylephrine 10. Increased contractility and heart rate, but decreased efficiency, were produced by isoproterenol, levarterenol, epinephrine, and phenylephrine. Isoproterenol was a vasodilator while the others were vasoconstrictors. Metaraminol produced increased myocardial contractility and increased efficiency. Phenylephrine had the least cardiac effect and was predominantly a peripheral vasopressor. (*Waldhausen, J. A., Kilman, J. W., and Abel, F. J.: Effects of Catecholamines on the Heart, Arch. Surg. 91: 86 (July) 1965.*)