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# TECHNICAL NOTE

## AN ITERATIVE METHOD FOR CALCULATING THE EFFECTS ON BLOOD $pO_2$ OF DILUTION WITH HEPARIN–SALINE SOLUTIONS*

WHEN performing a continuous analysis of blood parameters on line, the necessity of heparinizing the effluent stream of blood introduces the possibility of a change in some of the parameters of interest. The area of blood gas measurement is one which is complicated by this effect. By mixing a heparin–saline solution with the blood (for simplicity let us assume a 1:1 dilution) two liquids with different partial pressures of $O_2$ and $CO_2$ are brought together. Since it is required to know the partial pressure of oxygen in the blood ($pO_{2_B}$) and of carbon dioxide in the blood ($pCO_{2_B}$) and since the measurements must be performed on a diluted sample, the effects of this dilution must be calculated in order to relate the measured quantities ($pO_{2_S}$ and $pCO_{2_S}$) to the original quantities ($pO_{2_B}$ and $pCO_{2_B}$).

The original partial pressures are a function of the measured partial pressures and those of the heparin–saline solution ($pO_{2_H}$ and $pCO_{2_H}$).

Since the mechanisms of transport of $O_2$ differ from those of $CO_2$ in the blood, it might be expected that the effects of dilution upon the relation between the measured and true values will be different. The amount of $CO_2$ in solution, for example, is solely dependent upon its concentration and solubility in each solution. Since the concentration of $CO_2$ in the heparin–saline solution is small compared with that in the blood an effect would be expected which is proportional to the volume change. Thus, for a 1:1 dilution

$$pCO_{2_B} = 2pCO_{2_S}. \tag{1}$$

This has been verified experimentally by GAMBINO (1967).

The effects of dilution upon the $pO_2$ are more difficult to predict due to the highly non-linear mechanism involved in $O_2$ transfer. The high oxygen-binding capacity of the haemoglobin in the red blood cell is responsible for a reservoir of $O_2$ which has a smoothing influence on perturbations in $pO_2$. In other words, if $O_2$ is added to the plasma most of it would be transferred into the red blood cell and bound by the haemoglobin and the resulting rise in $pO_2$ will be very small. This occurs in the active range of the oxy-haemoglobin dissociation curve where the haemoglobin is not fully saturated. When the blood being monitored is venous blood, this will be the operating range. Conversely, if $O_2$ were removed from the plasma most of it would be replaced by the haemoglobin of the red blood cell and the drop in $pO_2$ will be minimized. This qualitative analysis of the effects of dilution upon the actual $pO_2$ of the blood must now be quantified to give meaning to the measured $pO_2$ for the cases when the heparin–saline solution has a higher $pO_2$ than the blood (this is so if the heparin–saline solution is in equilibrium with room air) and also when its $pO_2$ is less than that of blood (this can be achieved by bubbling pure $N_2$ through the solution to drive off the $O_2$). In both cases all solutions are maintained at 37°C and pH = 7·44. This eliminates the other variables which affect the oxy-haemoglobin dissociation curve.

One of the quantities which will be needed is the quantity of $O_2$ dissolved in the heparin–saline solution if it is in equilibrium with air at 37°C. This may be calculated by

$$\text{l.O}_2\text{/l. sol.} = \frac{pO_2}{P\text{total}} \times (\text{solubility of } O_2 \text{ in saline at } 37^\circ\text{ C}). \tag{2}$$

Where the solubility of $O_2$ in saline, which is approximately equal to that in plasma, is 0·023 and

$$pO_2 = \frac{\%\,O_2}{100}(760 - 47) = 0{\cdot}209\,(713) = 149 \text{ mmHg}. \tag{3}$$

(Note the correction factor of 47 for the vapour pressure of water.) Thus

$$\text{l.O}_2\text{/l. sol.} = \frac{149}{760}(0{\cdot}023)\,\text{l./l.} = 0{\cdot}00452\ \text{l.O}_2\text{/l. sol.}$$

For the case where pure $N_2$ is bubbled through the solution there will be no oxygen in solution.

To facilitate analysis of the partial pressure relationships in this dilution, it is convenient to consider the system divided into three compartments between which oxygen is free to flow. The first two compartments are the volumes of red blood cells and plasma respectively. The third is the volume of the diluent (in this case, a heparin–saline solution). See Table 1.

For nominal volumes of 1 l. of blood and 1 l. of diluent and a haematocrit of 0·45 the analysis proceeds as follows:

(1) Equilibrate the 1 l. heparin–saline solution with the 0·55 l. of plasma and calculate the $pO_2$ in 1·55 l. of this new solution.

(2) Remove (or add) $O_2$, as necessary, from this solution until the $pO_2$ of the remaining solution is equal to the expected $pO_2$ of the system at equilibrium.

(3) Add (or subtract) the $O_2$, which was removed (or added) in step (2), to the calculated $O_2$ in the 0·45 l. of RBC.

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*Table* 1. *Three-compartment model of system*

| 0·45 l. RBC | 0·55 l. Plasma | 1 l. Hep.–Sal. Sol. |
|---|---|---|
| $pO_{2_B}$ = | $pO_{2_B}$ ≠ | $pO_{2_H}$ |
| | ← $O_2$ → | |
| ← $O_2$ → | | |
| | $pO_{2_S}$ = | $pO_{2_S}$ |
| $pO_{2_S}$ | | |
| ← $O_2$ → | ← $O_2$ → | |
| $pO_{2_S}$ = | $pO_{2_S}$ = | $pO_{2_S}$ |

(4) Add that part of the $O_2$ still dissolved in the solution which is in the plasma compartment to the $O_2$ in the RBC to get total $O_2$ in 1 l. of blood (i.e. add 0·55/1·55 (l.$O_2$ in sol.) to l.$O_2$ in RBC).

(5) This yields the vol. per cent of $O_2$ in blood from which, with the aid of the proper curves, we get the per cent $O_2$ saturation and the $pO_2$ in the blood.

(6) If this $pO_2$ agrees with the expected $pO_2$ of part (2) the calculation is complete and this is the equilibrium $pO_2$ of the system.

(7) If this $pO_2$ is not equal to the expected $pO_2$ go back to part (2), modify the expected $pO_2$ in the proper direction and repeat steps (2–6), or (7) if necessary.

The curves needed are the oxy-haemoglobin dissociation curve and the $O_2$ concentration (in vol. %) vs. $pO_2$ curve (SEVERINGHOUSE, 1965). With a little practice the method is an easy way to calculate equilibrium conditions and usually requires only two or three iterations.

Example: Given,

| 0·45 l. RBC | 0·55 l. Plasma | 1 l. Hep. Sal. Sol. |
|---|---|---|
| $pO_2 = 40$ = | $pO_2 = 40$ ≠ | $pO_2 = 149$ |
| 74·5% sat. | | 0·00452 l.$O_2$ |
| 14·9 vol. % $O_2$ | | |

$T = 37°C$
pH = 7·44
sol. $O_2$ = 0·023

Find the $pO_{2_S}$ and per cent error.

(1) 1 l. hep.–sal. solution contains,

$$(0{\cdot}023)\frac{149}{760} = 0{\cdot}00452 \text{ l.}O_2$$

0·55 l. plasma contains,

$$(0{\cdot}023)\frac{40}{760}(0{\cdot}55) = 0{\cdot}000671 \text{ l.}O_2$$

$$0{\cdot}00452 + 0{\cdot}00067 = \frac{0{\cdot}00519\ O_2}{1{\cdot}55 \text{ solution}} = 0{\cdot}00335 \text{ l.}O_2/\text{l. sol.}$$

$$pO_2 = \frac{0{\cdot}00335\,(760)}{0{\cdot}023} = 110{\cdot}7 \text{ mmHg.}$$

(2) Since the diluent has a higher $pO_2$ than the $pO_{2_B}$ the final $pO_{2_B}$ will be greater than 40 mmHg. Assume it's 41·5 mmHg.

$$\frac{\text{l.}O_2}{\text{l. sol.}} = \frac{41{\cdot}5}{760}(0{\cdot}023) = 0{\cdot}001255 \text{ l.}O_2/\text{l. solution}$$

or 0·001949 l.$O_2$ in 1·55 l. of solution.
Thus l.$O_2$ transferred to RBC will be

$$0{\cdot}00519 - 0{\cdot}001949 = 0{\cdot}00324 \text{ l.}O_2.$$

$$(3)\ \text{l.}O_2 \text{ in } 0{\cdot}45 \text{ l. RBC} = \frac{0{\cdot}149 \text{ l.}O_2}{\text{l. blood}} - \frac{0{\cdot}000671 \text{ l.}O_2}{0{\cdot}55 \text{ l. plasma}}$$

$$= \frac{0{\cdot}14833 \text{ l.}O_2}{0{\cdot}45 \text{ l. RBC}}$$

$$0{\cdot}14833 + 0{\cdot}00324 = 0{\cdot}15157 \text{ l.}O_2/0{\cdot}45 \text{ l. RBC.}$$

$$(4)\ \frac{0{\cdot}55}{1{\cdot}55}(0{\cdot}001949) = 0{\cdot}000691 \text{ l.}O_2/0{\cdot}55 \text{ l. plasma.}$$

$$\frac{0{\cdot}15157 \text{ l.}O_2}{0{\cdot}45 \text{ RBC}} + \frac{0{\cdot}000691 \text{ l.}O_2}{0{\cdot}55 \text{ l. plasma}} = \frac{0{\cdot}152262 \text{ l.}O_2}{\text{l. blood}}.$$

(5) 15·2262 vol. per cent $O_2$ → $pO_2$ = 41·5 mmHg
→ 76·2% $O_2$ saturation.

(6) 41·5 mmHg from (5) agrees with expected value from (2).

At equilibrium

| 0·45 l. RBC | 0·55 l. Plas. | 1 l. Sol. |
|---|---|---|
| 0·15157 l.$O_2$ | 0·000691 l.$O_2$ | 0·001257 l.$O_2$ |
| | 15·2 vol. % $O_2$ | 0·001948 l.$O_2$ |
| 76·2% sat. | | |
| $pO_2 = 41{\cdot}5$ | = $pO_2 = 41{\cdot}5$ | = $pO_2 = 41{\cdot}5$ |

Note: while curves may be used to obtain values, nomographs are more accurate and easier to read. Also, a slide rule is very useful for setting up proportions and reading off the values of interest (i.e. set 14·9 vol. per cent on *C* scale over 74·5% sat. on *D* scale and for new vol. per cent of 15·22 on *C* scale read new per cent sat. (76·2) on *D* scale).

The per cent error is therefore,

$$\%\,E = \frac{(pO_{2_S} - pO_{2_B})}{pO_{2_B}} \times 100 = \frac{1{\cdot}5}{40}(100)$$

$$= 3{\cdot}75 \text{ per cent.}$$

Figures 1 and 2 show the results of dilution on various values of $pO_{2_B}$. Although the magnitude of the error is less with a diluent whose $pO_2$ is zero, the variation of the

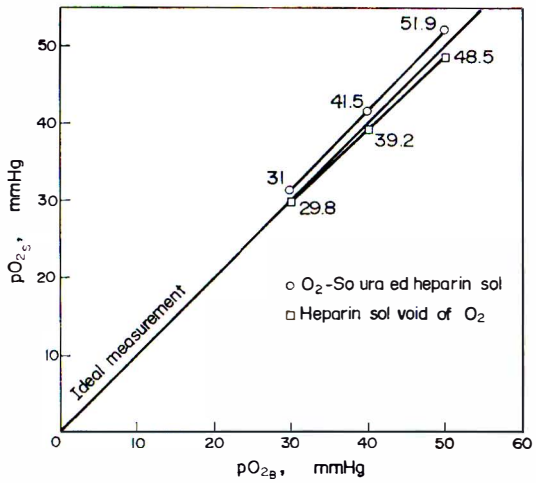


FIG. 1. Partial pressure of oxygen in the withdrawn solution related to that of the blood.

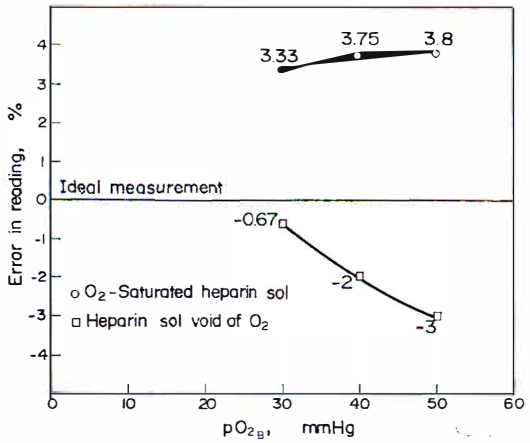


FIG. 2. The percentage error in the reading of the oxygen pressure in solution related to the partial pressure of oxygen in the blood.

error as a function of $pO_{2_B}$ is less for the case where the $pO_{2_H}$ is high. This is an advantage since a nominal error can be assumed for a given range of $pO_{2_B}$ and no special procedure will be necessary to obtain a high $pO_{2_H}$.

The above analysis has also been verified experimentally by GAMBINO (1967).

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