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ABSTRACT—The oxygen equilibrium curves of human fetal and adult hemoglobins were reconstructed from the published Adair constants. The curves were then analyzed theoretically with respect to the amount of transferred oxygen, which is directly related to the saturation difference ($\triangle S$) of hemoglobin with oxygen in the artery and vein. In fetal blood, the oxygen affinity is optimized so as to provide the maximal $\triangle S$ value in the fetus oxygen environment. In adult blood, on the other hand, the $\triangle S$ value is far smaller than the theoretically obtained maximum, but it is most sensitive to the P_{50} changes around its physiological value of 27 torr. The present results imply that adult blood reserves an oxygen transport capacity for increased oxygen demands under resting conditions, and that the oxygen affinity is optimized so as to make the Bohr effect most effective to gaseous exchange.

INTRODUCTION

The oxygen equilibrium curve (OEC) of hemoglobin (Hb) can be characterized in terms of its position, which is usually expressed by the oxygen pressure at half saturation of Hb with oxygen (P_{50}), as well as of its shape, which is quantitatively expressed by the highest slope of the Hill plot (n_{max}). The position of OEC is shifted on changes in the pH or the concentration of organic phosphates in red blood cells.

In our previous paper (Kobayashi *et al.*, 1994a), we have reported on the significance of the slope of OEC in the oxygen transport efficiency of Hb. The efficiency was expressed by the quantity S' ($=dS/dP$), where S and P denote the oxygen saturation and the partial pressure of oxygen, respectively, and the plot of S' against P yielded a bell-shaped curve. The ordinate and abscissa readings of the maximum point in the curve give the maximal oxygen transport efficiency, S'_{max}, and the corresponding partial pressure of oxygen, P_{dmax}, respectively. The P_{dmax} value for human fetal whole blood was found to be 17 torr under physiological conditions and it corresponds to the steepest part of the OEC. It seems that fetal blood is best adapted to its physiological conditions with the partial pressure of oxygen between 35 and 15 torr and consequently not well to severe hypoxic conditions. On the other hands, the P_{dmax} value of 22 torr found for the whole blood of human adult under resting physiological conditions (giving S=0.38), was definitely lower than the oxygen pressure

in the mixed venous blood (40 torr). It was therefore concluded that a considerable portion of the oxygen transport capacity of adult blood is reserved for large oxygen demand that may occur under severe exercise conditions.

In this paper, the difference in arterio-venous oxygen saturation, $\triangle S$, and its differential value of $d\triangle S/dP_{50}$ were calculated as new indices for oxygen transport function, and a theoretical examination was made on the significance of the P_{50} values of fetal and adult blood.

MATERIALS AND METHODS

The experimental data used for the present analysis were of 40 OEC data sets previously published for human adult and fetal hemoglobins (Imai, 1982; Imai and Yonetani, 1975; Imaizumi *et al.*, 1982; Tyuma *et al.*, 1973). Human adult Hb consists of the two α-subunits and two β-subunits, whereas fetal Hb consists of two α-subunits and two γ-subunits. Fetal Hb shows an oxygen affinity considerably higher than that of adult Hb, and thus oxygen is transferred to fetal blood effectively through the placenta. In this paper, the OECs were also reconstructed using the published values of Adair constants. According to Adair (Adair, 1926), the oxygen saturation (S) of tetrameric Hb is expressed as a function of oxygen pressure (P) as follows:

$$S=(K_1P + 3K_1K_2P^2 + 3K_1K_2K_3P^3 + K_1K_2K_3K_4P^4)/$$
$$(1 + 4K_1P + 6K_1K_2P^2 + 4K_1K_2K_3P^3 + K_1K_2K_3K_4P^4) \quad (1)$$

where K_i (i=1 to 4) is the intrinsic constant (Adair constant) at i th oxygenation step.

All computations were carried out on a personal computer model PC-9821 Ap2 (Nippon Electric Co., Tokyo) using MS-FORTRAN.

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RESULTS AND DISCUSSION

Calculation of △S and comparison of the shape of OEC between fetal and adult Hb

The Adair constants of Hbs have been determined with reasonable accuracy from precise oxygen equilibrium data (Imai, 1982; Imai and Yonetani, 1975; Imaizumi *et al.*, 1982; Tyuma *et al.*, 1973), which makes it possible to analyze the OECs quantitatively. First, we defined △S as difference in the S values of the artery and vein. For adult blood, we used the literature values of 100 and 40 torr as the arterial and venous P, respectively (Altman and Ditter, 1975). The arterio-venous difference in S was designated as $△S_{(100-40)}$. For fetal blood, the corresponding literature values were 35 and 15 torr, respectively (Breathnach, 1991). The difference in S for fetal blood was designated as $△S_{(35-15)}$. Figure 1 shows an example of the calculation of the △S value. The hypothetical OECs with different P_{50} values were constructed from the reported Adair constants (ki, $i=1$ to 4) which were changed by common factors, *i.e.* $ki → ki$·constant ($i=1$ to 4). By doing this, the position of OEC was shifted freely without change in its shape. Unfortunately, only a few accurate OEC data sets are available for fetal Hb (Tyuma *et al.*, 1973). In Fig. 2, the product of $S'·P_{50}(=dS/d(P/P_{50}))$ was plotted against P/P_{50}. The P and S' values were normalized by dividing by P_{50} to eliminate the effect of P_{50} difference on the shape of OEC (Kobayashi *et al.*, 1994b). Figure 2 shows a close similarity in the shape of OEC between fetal Hb (A) and adult Hb (B). This accords with the earlier finding of Allen *et al.* (1953) that there is no significant difference in the shape of OEC between fetal and adult Hb.

△S vs. P_{50} plot for oxygen environment of fetal and adult blood

Figure 3A shows the dependence of $△S_{(35-15)}$ on P_{50} calculated for hypothetical OECs with $n_{max}=3.2$ for fetal blood. The value of $△S_{(35-15)}$ reached a maximum ($△S_{(35-15)max}$) at $P_{50} = 22$ torr. The theoretically obtained optimum P_{50} value was very close to the actual P_{50} value (20 torr) for the fetal blood under physiological conditions.

Figure 3B shows the amount of oxygen released in adult vein (△S) as a function of P_{50}. The P values in artery and vein were assumed to be 100 and 40 torr, respectively. The $△S_{(100-40)}$ reached a maximum ($△S_{(100-40)max}$) value of 0.52 at $P_{50}=62$ torr. This was much higher than the $△S_{(100-40)}$ value of 0.23 calculated at $P_{50}=27$ torr for adult blood under the physiological conditions.

S' vs. P plot for oxygen environment of fetal and adult blood

Figure 4A shows an S' vs. P plot calculated for the OEC of fetal ($P_{50}=20$ torr) blood under the physiological conditions. The OEC changes steeply in the fetal oxygen environment (35-15 torr), and the maximum point for S' was found within the physiological P range. This implies that fetal blood provides constantly a maximum oxygen-transport efficiency and has almost no reserve for increased oxygen demands.

By using the classical Hill equation, Willford *et al.* (1982) theoretically examined the optimal position of fetal Hb OEC at which the maximum amount of oxygen can be released from Hb. They showed that the optimal P_{50} can be expressed as the square root of the product of arterial and venous P values. The calculated P_{50} value for the present case was 23 torr, this being slightly greater but very close to the optimum P_{50} value (22 torr) noted above.
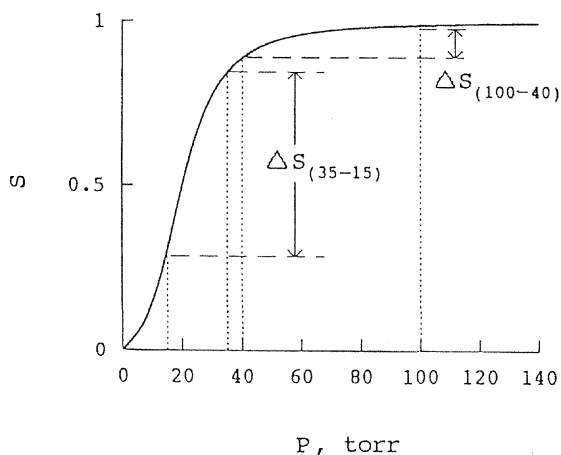
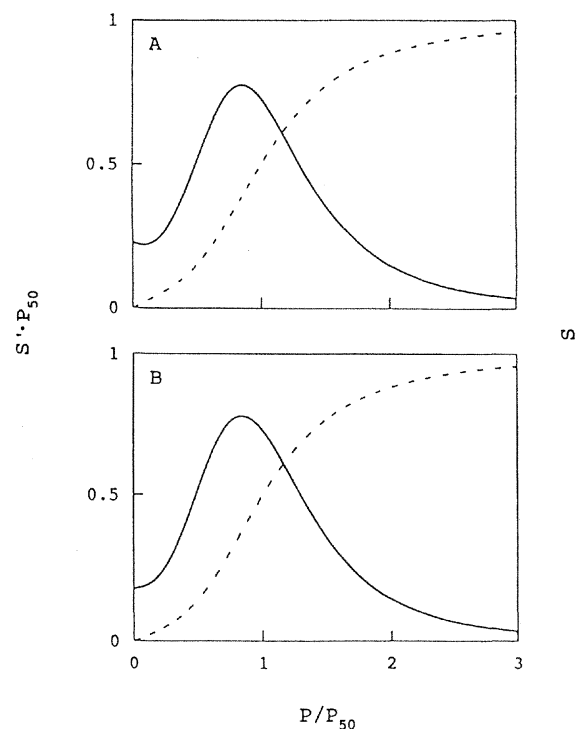On the other hand, the S' vs. P plot for OEC ($P_{50}=27$ torr)

Fig. 1.   Example of △S calculation. $△S_{(100-40)}$ is for adult blood and $△S_{(35-15)}$ is for fetal blood. OEC data set used for the calculation were taken from Imai (1982).

Fig. 2.   S vs. P/P_{50} (dashed lines) and $S'·P_{50}$ vs. P/P_{50} (solid lines) plots for human fetal (A) and adult (B) Hb. OEC data sets used for calculation were taken from Tyuma *et al.* (1973), and from Imai and Yonetani (1975).
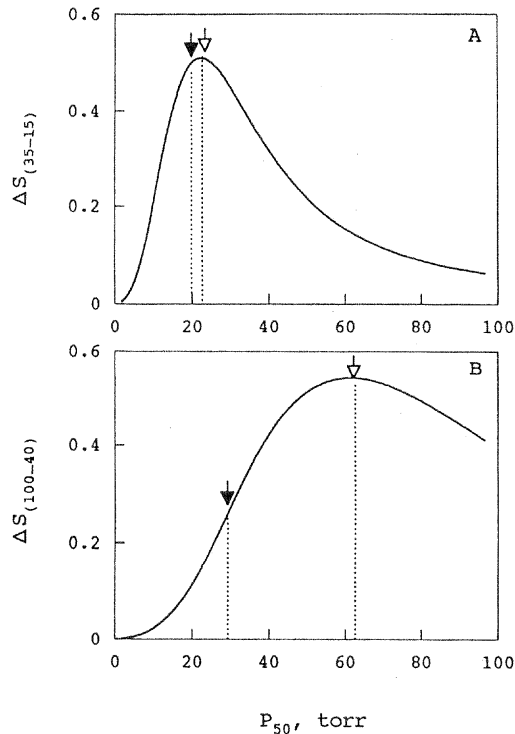
Fig. 3. (A) The effect of P_{50} on saturation difference, $\triangle S_{(35-15)}$, in physiological oxygen environment of fetal blood. (B) The effect of P_{50} on arterio-venous saturation difference, $\triangle S_{(100-40)}$, in physiological oxygen environment of adult blood. (open arrow) theoretically obtained optimum P_{50} and (closed arrow) physiological P_{50}. OEC data set used for the calculation were taken from Imai (1982).
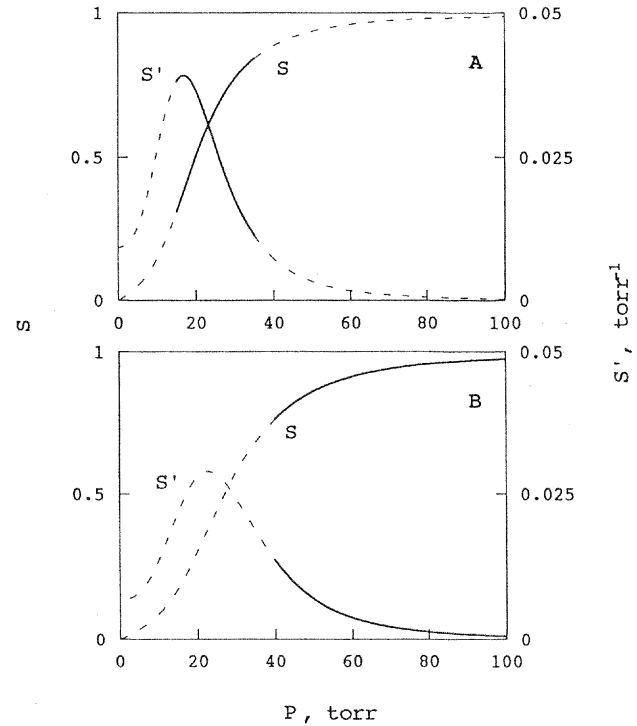

Fig. 4. S' vs. P plots for fetal (A) and adult (B) blood. Solid lines indicate S and S' under physiological oxygen environment of fetal (35-15 torr) and adult (100-40 torr) blood. The OEC data set used for the calculation are the same as in Fig. 3.

of adult blood under physiological conditions is shown in Fig. 4B. As seen in the figure, the S' value at adult venous P (40 torr) is low, this implying that under resting conditions the advantage of cooperativity is scarcely utilized. However, under hard exercise conditions, P will probably decrease to near 20 torr, which is almost equal to the P_{dmax} value (22 torr) of OEC with P_{50} = 27 torr. Figure 4B also indicates that, in adults, the gradual increase in the S' value occurs at P below 40 torr, and adult blood is regarded as holding a reserve to meet the increase in the oxygen demand during severe exercise.

Another significance of adult blood P_{50}

In the physiological oxygen environment for adult blood, the maximum value of $\triangle S$ is obtained at P_{50} =62 torr (Fig. 3B). However, a blood with this P_{50} value cannot fill an increased oxygen demands any more. To find the significance of the P_{50} of the adult blood, we have calculated the first derivatives of $\triangle S_{(100-40)}$ with respect to P_{50} (d$\triangle S_{(100-40)}$/dP_{50}) as a function of P_{50} (Fig. 5A), and found that the value of d$\triangle S_{(100-40)}$/dP_{50} reached a maximum at P_{50} = 29 torr. This implies that $\triangle S_{(100-40)}$ is most sensitive to P_{50} change at P_{50} =29 torr. It should be noted that the theoretically obtained optimum P_{50} value (29 torr) is nearly equal to the experimental P_{50} (27 torr) of the adult blood under the physiological conditions. To

ascertain the results, the same calculation was carried out for the 38 OEC data sets of human adult Hb (Imai, 1982; Imai and Yonetani, 1975; Imaizumi *et al.*, 1982; Tyuma *et al.*, 1973) giving different values of n_{max}. It was found that the P_{50} values which give the maximum d$\triangle S_{(100-40)}$/dP_{50} fell in a narrow range from 27 to 31 torr (Fig. 6).

The change in the position of OEC, which actually occurs in the physiological conditions, is known as the Bohr effect. Metabolically produced CO_2 acidifies the blood in the tissue capillaries, causing a rightward shift of the OEC that in turn promotes oxygen release (see the broken line of Fig. 5A). The magnitude of the Bohr shift is expressed by the Bohr coefficient ($\triangle \log P_{50}$/$\triangle$pH). Our present analysis shown in Fig. 5A indicates that the human adult blood with P_{50}=27 torr is designed to make the Bohr shift most efficient at the arterial P of 100 torr and the venous P of 40 torr.

In the oxygen environment of fetal blood, the value of d$\triangle S_{(35-15)}$/dP_{50} reaches a maximum when P_{50} is 13 torr (Fig. 5B). At P_{50} of 20 torr, the value of d$\triangle S_{(35-15)}$/dP_{50} is far below the maximum, though its value is still not very small compared with the adult one. It should be pointed out that, in the fetal blood, the Bohr effect still plays an important role in CO_2 transport by generating a large arterio-venous difference in CO_2 content.
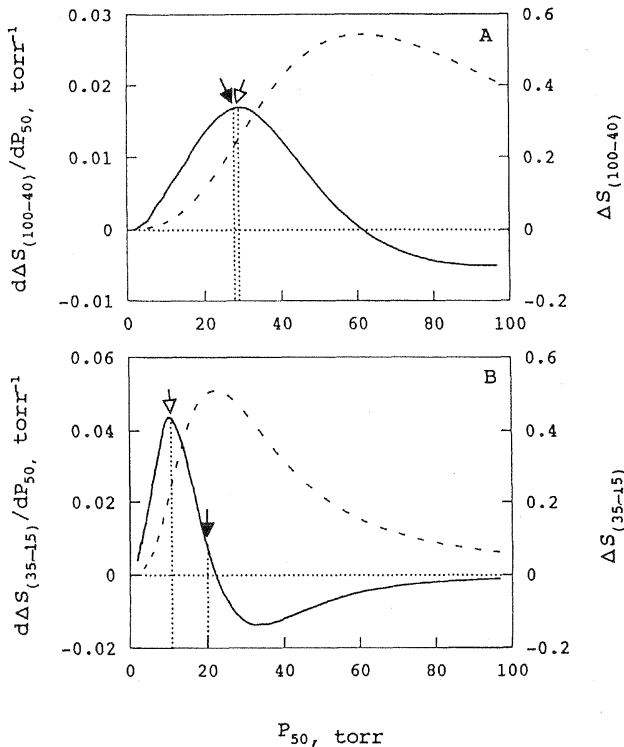
Fig. 5. The first derivative for the arterio-venous saturation difference, $d\triangle S/dP_{50}$, for adult (A) and fetal (B) blood plotted against P_{50}. (open arrow) theoretically obtained optimum P_{50} and (closed arrow) physiological P_{50}. The OEC data set used for the calculation are the same as in Fig. 3.
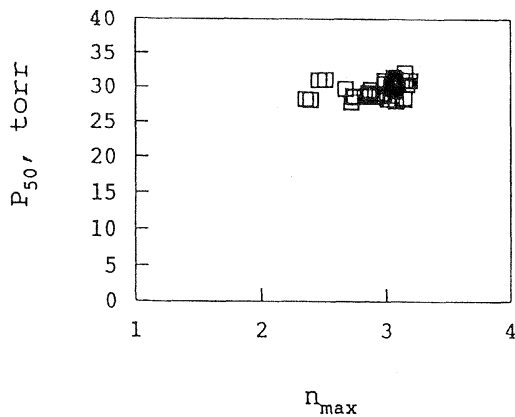

Fig. 6. The plot of P_{50} values that maximizes $d\triangle S_{(100-40)}/dP_{50}$ against the n_{max} values. The OEC data sets used for the calculation were taken from Imai (1982), Imai and Yonetani (1975), Imaizumi *et al.* (1982) and Tyuma *et al.* (1973).

In conclusion, the fetal blood is designed to optimize the P_{50} so that $\triangle S_{(35-15)}$ is maximized, whereas the adult blood is designed so as to keep a reserve for oxygen demands at exercise and to make the Bohr effect most effective under resting conditions.

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