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Spectrophotometric monitoring of arterial oxygen saturation in the fingertip

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Abstract—*A noninvasive oximeter that analyses the oxygen saturation of arterial blood in the fingertip is described. The light, after attenuating the infrared portion to avoid thermal injury, is applied to the fingertip through an optical transmitter made of glass fibres. The transmitted light is transferred to an optical reception system where a spectrophotometric determination of oxygen saturation is performed. The determination is performed by considering only the change in the attenuation of light caused by the inflow of arterial blood into the fingertip. The correlation between the oxygen saturation measured with the present instrument (y) and that with the blood-gas method (x), was $y = 0{\cdot}907x + 8{\cdot}592$ with a standard deviation and a correlation coefficient of 0·135% and 0·983, respectively. The reproducibility was assessed in a healthy subject by measuring the oxygen saturation repeatedly 60 times. The mean saturation was $95{\cdot}82 \pm 0{\cdot}675\%$ (mean ± standard deviation). The instrument has been useful in monitoring arterial oxygenation in patients with respiratory failure in our intensive-care unit. One of the disadvantages of the instrument is that the measurement is interrupted when the fingertip changes its position against the light beam.*

Keywords—*Glass-fibre optic, Noninvasive respiratory monitor, Oximeter*

1 Introduction

NONINVASIVE blood-gas monitoring is essential to the patient with respiratory failure. However, there are only a few monitoring devices that are noninvasive and have a high precision and stability. A noninvasive *in vivo* oximeter (OXIMET model MET 1471, Mochida Pharmaceutical Co. Ltd., Tokyo), which performs the spectrophotometric analysis of the transmitted light through the fingertip, has been recently developed. It measures the oxygen saturation of arterial blood by analysing the change in the optical density of the transmitted light with

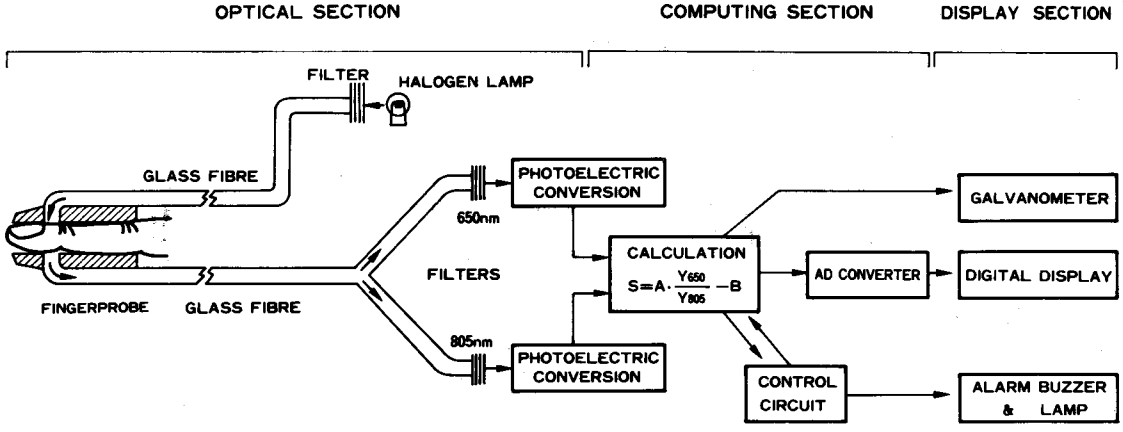

Fig. 1 Block diagram of the instrument
Light emitted by the halogen lamp is transferred by the glass fibres and applied to the fingertip. The transmitted light is led through 650 and 805 nm filters reaching photocells that convert the light energy into an electrical signal. The computer section calculates S, as shown in Fig. 3. The control circuit determines if the photoelectric output is adequate for the analysis or not. See text and Fig. 3

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the inflow of arterial blood into the fingertip. In the present paper we describe the principle of operation as well as the functional characteristics of the present instrument. Problems encountered in its clinical application are also discussed.

2 Principle of operation

The light emitted by a halogen lamp is applied to the fingertip through an optical transmitter made of glass fibres. The transmitted light is led to an optical reception system where the spectrophotometric analysis is performed (Fig. 1).

The oxygen saturation of the whole blood can be derived from the following well known equation (WOOD, 1949; GORDY and DRABKIN, 1957):

$$S = A - B\frac{\alpha_{650}}{\alpha_{805}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where α_{650} and α_{850} are the absorption coefficients of the whole blood at the wavelengths of 650 and 805 nm. A and B are constants related to the absorption coefficients of haemoglobin and oxyhaemoglobin, respectively.

The present instrument employs the following principle in measuring the oxygen saturation of arterial blood in the fingertip. It is necessary to be concerned only with the attenuation of light by the arterial blood from that of the complete fingertip, which consists of a 'blood' compartment (arterial and venous blood) and a 'nonblood' compartment (skin, muscle, bone, connective tissues etc.). The attenuation of light by the 'nonblood' compartment hardly changes with pulsation. The 'blood' compartment, on the other hand, changes its volume as the blood flows into and out of the vascular bed with pulsation. Accordingly, the optical density of the transmitted light fluctuates, as shown in Fig. 2. Assuming the increase in the attenuation of light is caused solely by the arterial blood that flows into the fingertip during the inflow phase, we can calculate the oxygen saturation of the arterial blood by subtracting the d.c. component of the attenuation from the total attenuation by the fingertip, leaving only the a.c. component for the spectrophotometric analysis of the oxygen saturation.

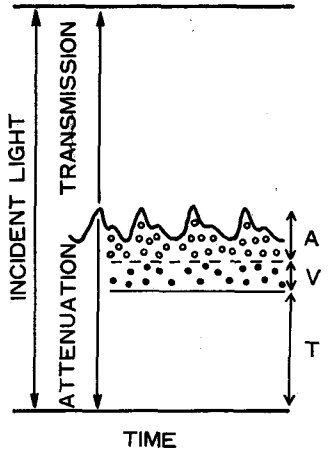

Fig. 2 Schematic of the pulsatile photoelectric output. The attenuation of the incident light is caused by A = arterial blood, V = venous blood, T = tissues

Assuming that Beer's law is valid for the whole blood that is present in the fingertip, and that the attenuation of light by multiple scattering, refraction and reflection can be neglected, the optical density of the transmitted light I can be written as

$$I = I_0 F_T 10^{-\alpha' d} 10^{-\alpha l}$$

where I_0 is the optical density of light incident to the fingertip, F_T is the rate of absorbance of light by the 'nonblood' compartment, d and α' is the quantity of blood that is present at the end of the outflow phase and its absorption coefficient, l and α is the quantity of arterial blood that flows into the fingertip and its absorption coefficient.

The total output of the photoelectric element E_{DC+AC} is given by

$$E_{DC+AC} = AI = AI_0 \gamma F_T 10^{-\alpha' \gamma d} 10^{-\alpha \gamma l}$$

where A and γ are constants specific to the photoelectric element.

Similarly, the d.c. component of the photoelectric output is given by

$$E_{DC} = AI_0 \gamma F_T 10^{-\alpha' \gamma d}$$

The logarithmic difference of E_{DC+AC} and E_{DC} is

$$Y = \log(E_{DC+AC}/E_{DC}) = -\alpha \gamma l$$

The Ys at the wavelenths of 650 and 805 nm (Y_{650} and Y_{805}, respectively) are calculated as follows:

$$Y_{650} = -\alpha_{650} \gamma l$$

$$Y_{805} = -\alpha_{805} \gamma l$$

Therefore

$$\alpha_{650}/\alpha_{805} = Y_{650}/Y_{805}$$

In this manner, the ratio of the absorption coefficients at the wavelengths of 650 and 805 nm is determined by measuring the ratio of Ys at the respective wavelengths. Accordingly, in terms of Y_{650}/Y_{805}, eqn. 1 can be rewritten as

$$S = A - B\frac{Y_{650}}{Y_{805}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

3 Description of the instrument

The instrument consists of optical, computing and display sections, as shown in Fig. 1.

3.1 *Optical section*

A halogen lamp is used as the light source. The light emitted is filtered with a broadband filter that attenuates infrared radiant energy so as to avoid thermal injury to the fingertip. The light is then carried by an optical transmitter (glass-fibre optic) 2 m in length to a finger probe made of silicone rubber. The transmitted light passes through another glass fibre until it enters an optical reception system, where the light is bisected and led through narrow-band filters that selectively transmit light at the wavelengths of 650 and 805 nm. The light is then led to a pair of photocells where the photoelectric conversion is taken place (Figs. 1 nad 3). The spectral transmittance curves of the filters and the spectral emittance curve of the halogen lamp are illustrated in Fig. 4.

3.2 *Computing section (Fig. 3)*

The computing section calculates the arterial oxygen saturation using eqn. 2. A simplified circuit diagram is illustrated in Fig. 3. The output of Q1(E_{DC+AC}) is introduced into Q2, while the mean of the output voltage of Q1 (E_{DC}) is applied to the input terminal of Q3. The logarithmic conversion and subtraction are accomplished by a combination of Q2, TR1, Q3 and TR2 calculating $Y = \log (E_{DC+AC}/E_{DC})$. The result is then introduced through an amplifier (Q4), a highpass filter (h.p.f.), a gain controller and a lowpass filter (l.p.f.), to a rectifier and an integrator (Q8, D3, D4, Q9, TR3, and TR4) where the mean of the 5 s signal is obtained. Up to this point, duplicate circuits function for each of the two wavelenths. A division circuit (Q10, TR5, TR6, Q11, Q12, TR7, TR8, and Q13) then calculates the oxygen saturation S from Y_{650} and Y_{805} according to eqn. 2. Values for A and B are calculated from the absorption coefficients of haemoglobin and oxyhaemoglobin reported by HORECKER (1943). Variable resistors VR1 and VR2 are adjusted so as to obtain appropriate values of saturation when the calculated values of Y_{650}/Y_{805} for the oxygen saturation of 70, 80, 90 and 95% are applied to Q13. The output of the division circuit (output of Q13) is held for 5 s with a sample-and-hold circuit that is connected to an analogue-digital convertor (a.d.c.). The control circuit switches the input to the sample-and-hold circuit on or off according to the amplitude of the oscillatory output of l.p.f. When either the output of l.p.f. is smaller than 500 mV or a sudden drift of the output occurs, the input to the sample-and-hold circuit is disconnected and the display goes out. The control circuit also serves as an alarm system that functions when the oxygen saturation becomes lower than a preset trigger level.

A sinewave generator is incorporated in the instru-

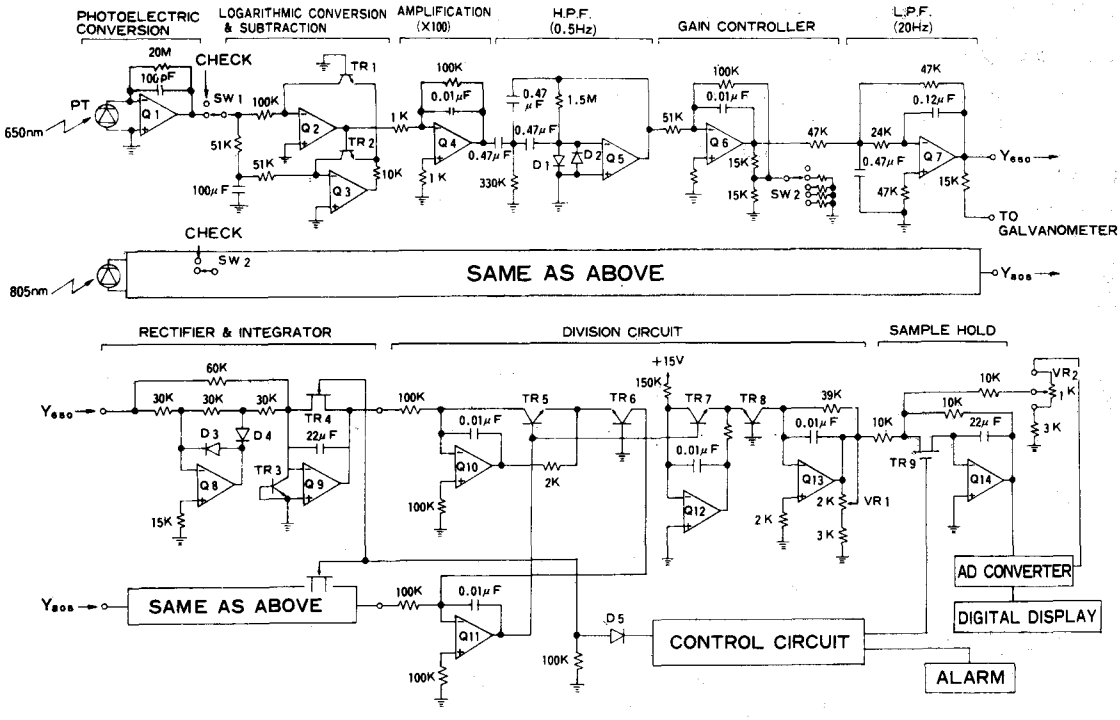

Fig. 3 Circuit diagram of the computing section of the instrument. Integrated circuits are general-purpose operational amplifiers such as model μA741. PT is a phototransistor EE-D66 (Tateishi Electronics Co. Ltd.)

ment to check the performance of the electrical circuit. When the signals from the generator are selected by means of selector switches, SW1 and SW2, the digital meter shows 90% provided the circuit functions normally.

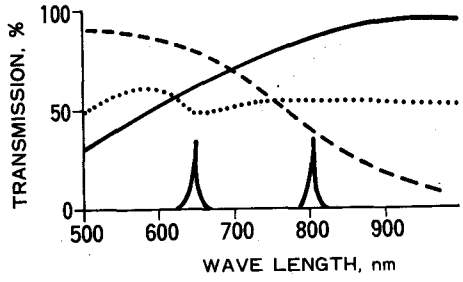

Fig. 4 Spectral transmittance curve of the broadband filter (broken line), the glass fibres (dotted line) and the narrowband filters (solid lines at 650 and 805 nm) and a spectral emittance curve of the halogen lamp (solid line)

3.3 *Display section (Fig. 5)*

The instrument has a digital meter on which the oxygen saturation is displayed every 5 s. On the front panel there is a galvanometer and an attenuator. The level of the photoelectric output is controlled by the attenuator and displayed on the galvanometer.

4 Performances of the instrument

4.1 *Linearity*

The linearity of the instrument was assessed by measuring the oxygen saturation of 53 arterial blood samples taken from 15 patients who were admitted to the Intensive Care Unit, Osaka University Hospital between June 1977 and December 1977.

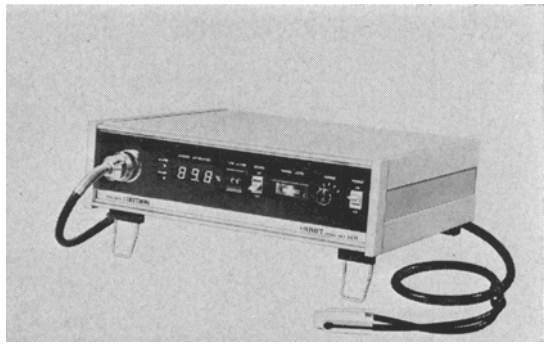

Fig. 5 Front view of the instrument
From left to right are: an optical transmitter (a pair of 2 m cables made of glass fibres with a fingerprobe), alarm and ready lamps, a digital meter, a trigger level controller, an alarm buzzer switch, a galvanometer, an attenuator and a power switch

The mean haematocrit of the blood samples was 36·40 with a standard deviation of 4·76. Oxygen saturation values of the blood samples were derived from the partial pressure of oxygen and the pH measured with a Radiometer blood gas analyser (model BMS–MK2 and PHM 71–MK2) using a nomogram described by SEVERINGHAUS (1966).

The correlation between the oxygen saturation values measured with the present instrument (y–ordinate) and with the Radiometer equipment (x–abscissa) is shown in Fig. 6. The correlation equation is $y = 0{\cdot}907x + 8{\cdot}592$ with a standard deviation and a correlation coefficient of 0·135 and 0·983, respectively. The oxygen saturation measured with the present instrument is within ±5% of that obtained from the blood-gas method.

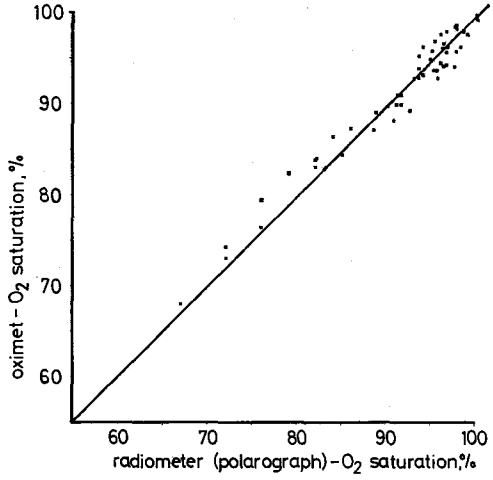

Fig. 6 Comparison of oxygen saturation measured with the present oximeter (ordinate) and the blood-gas method (abscissa). The diagonal line is of identity

4.2 *Reproducibility*

The reproducibility of the instrument was assessed by measuring the arterial oxygen saturation of a normal volunteer repeatedly 60 times while the subject breathed air quietly. The mean oxygen saturation was 95·82% with a standard deviation of 0·675. However, the reproducibility could be obtained only when the fingertip was stationary in the finger probe. When the fingertip changed its position against the lightbeam, the readings either fluctuated or the computer section ceased to calculate the oxygen saturation because of the sudden disturbance of the photoelectric output.

4.3 *Response*

The time delay due to both the optical and computing sections is negligibly small. However, the display section has a time delay of 5 s because it

displays the oxygen saturation as the mean value of 5 s saturation, as described above.

4.4 *Influences of the circulatory change*

We studied the influence of the circulatory state of the fingertip on the photoelectric output and digital readout of the present instrument. A sphygmomanometer cuff was applied to one of the upper arms of a healthy volunteer. Stepwise increments in cuff pressure were produced as shown in Fig. 7. The subject had a blood pressure of 124/60 mmHg when the measurement was performed. Until the cuff pressure was increased to 90 mmHg, there were no gross changes in either the photoelectric output or the oxygen saturation. When the cuff pressure was increased to 100 and 110 mmHg, the pulse-wave contours of the photoelectric output became damped, while the digital display gave reasonable values. When the cuff pressure was increased to 120 mmHg, which was 4 mmHg lower than the systolic blood pressure, the photoelectric output was decreased to less than 500 mV in amplitude. The display section ceased to function in this case. At a cuff pressure of 130 mmHg, neither the pulsatile output nor the digital display were obtained.

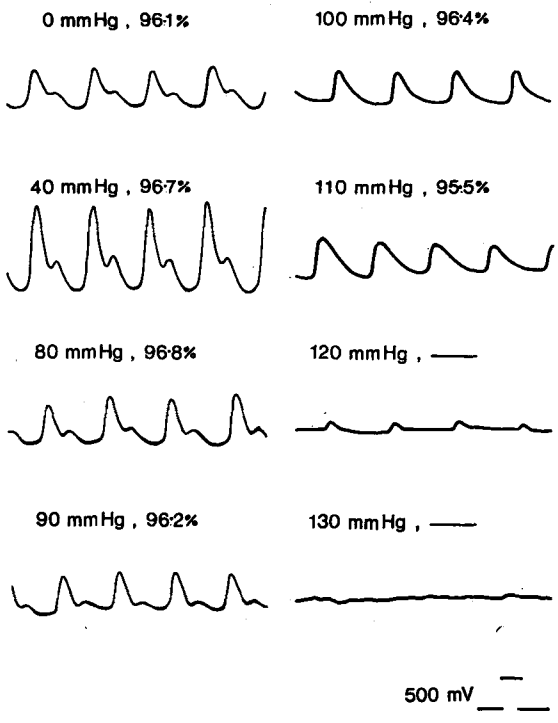

Fig. 7 Photoelectric output of a healthy subject when a sphygmomanometric cuff applied proximal to the finger was inflated in a stepwise fashion. The figures on each tracings are the cuff pressure and digital readout of the instrument, respectively

5 Discussion

The present instrument performs the spectrophotometric analysis of the transmitted light through the fingertip. Theoretically, Beer's law for the absorption of light by the haemoglobin or haemolysed blood is not valid for the nonhaemolysed blood and tissues because the attenuation of light is caused not only by the absorption but also by the scatter, refraction and reflection by the blood constituents and tissues (NILSSON, 1960). In practice, however, the oxygen saturation of whole blood that is present in the tissue can be measured because the attenuation of light by the scatter, refraction and reflection is largely cancelled by the spectrophotometric analyses at two different wavelengths.

WOOD (1949) successfully measured the absolute saturation value directly by subtracting the light absorption of the bloodless ear from that of the blood-containing ear. This method needs the application of radiant heat to arterialise the blood in the ear. The present instrument employs a similar principle in measuring the absolute saturation to that of the compression method described by Wood. It subtracts the d.c. component of the attenuation of light by the fingertip (instead of the bloodless tissue) from the total attenuation of light, which fluctuates as the arterial blood flows into and out of the fingertip. Since the difference in the attenuation of light is caused solely by the arterial blood, neither the compression nor the arterialisation of the fingertip are necessary. Another advantage to the present method is that the determination of the oxygen saturation is not influenced by the instability of the light source because of the subtraction method using two different wavelengths.

An ear oximeter that is based on the similar principle has been developed simultaneously and independently (NAKAJIMA *et al.*, 1975). The transducer of the ear oximeter consists of a light emitting element, optical filters and photocells. Since the transducer is directly attached to the ear, the possibility of the thermal injury to the ear cannot be excluded. The present instrument, on the other hand, delivers the incident light to the fingertip through a glass-fibre optic. The light source and the optical filters are incorporated in a chassis along with the electrical circuit enabling the more selective spectrophotometry with the cool light. With this method, there is hardly any possibility of thermal injury and electrical macroshock to the patient.

The accuracy and reproducibility of the present instrument is adequate for its use as a respiratory monitor. However, the instrument is of limited application under the circumstances where the pulsation in the fingertip is very weak. For instance, we could not obtain sufficient photoelectric output in patients who underwent assisted circulation using an extracorporeal membrane oxygenator for severe respiratory failure. Similarly, in patients whose

circulatory states were progressively deteriorating, the instrument showed erroneous readings.

The standard oxygen dissociation curve of haemoglobin cannot be used when the blood pH is abnormally high or low, because the oxygen affinity of haemoglobin is considerably affected by the concentration of 2,3-diphosphoglycerate (2,3-DPG), which is altered with an abnormal pH (OKADA *et al.*, 1977). In patients with severe acidosis, the oxygen saturation of arterial blood measured with the present instrument differed as much as 10% from that obtained with the blood-gas method. We excluded these patients from the study because we did not measure 2,3-DPG in the present study.

For the evaluation of arterial oxygenation by the lungs, monitoring of the arterial oxygen tension is more reasonable than that of the arterial oxygen saturation. However, most devices are invasive and require arterial cannulation. A noninvasive transcutaneous oxygen electrodes has been developed in Europe that is useful in monitoring arterial oxygen tension in newborn infants in whom multiple arterial punctures are troublesome (PEABODY *et al.*, 1978; LE SOUËF *et al.*, 1978).

The oxygen saturation of arterial blood, on the other hand, is a useful parameter in monitoring how much oxygen is carried by the blood to the peripheral tissues. Since alveolar hyperoxia brings about pulmonary oxygen toxicity (WINTER and and SMITH, 1972), the inspiratory oxygen concentration should desirably be reduced below 40% even in the presence of a severe respiratory failure. In this sense, we consider that we should use the lowest concentration of inspiratory oxygen so long as the arterial oxygen saturation of 90% is guaranteed. The present instrument is useful in monitoring the oxygen saturation in these patients.

One of the disadvantages of this instrument is that the measurement is interrupted when the fingertip changes its position against the light beam. This frequently occurs when the patient is shivering and/or unco-operative. The instrument would be more useful if this problem could be overcome.

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References

GORDY, E. and DRABKIN, D. L. (1957) Spectrophotometric studies XVI: determination of the oxygen saturation of blood by a simplified technique available to standard equipment. *J. Biol. Chem.*, **227**, 285–296.

HORECKER, B. L. (1943) The absorption spectra of haemoglobin and its derivatives in the visible and near infra-red regions. *J. Biol. Chem.*, **148**, 173–183.

LE SOUËF, P. N., MORGAN, A. K., SOUTTER, L. P., REYNOLDS, E. O. R. and PARKER, D. (1978) Continuous comparison of transcutaneous and arterial oxygen tension in newborn infants with respiratory illnesses. *Acta Anaesth. Scand. Suppl.*, **68**, 91–97.

NAKAJIMA, S., HIRAI, Y., TAKASE, H., KUSE, A., AOYAGI, S., KISHI, M. and YAMAGUCHI, K. (1975) New pulsed-type earpiece oximeter. *Kokyu to Junkan*, **23**, 709–713.

NILSSON, N. J. (1960) Oximetry. *Physiol. Rev.*, **40**, 1–26.

OKADA, Y., TYUMA, I. and SUGIMOTO, T. (1977) Evaluation of Severinghaus' equation and its modification for 2,3-DPG. *Jap. J. Physiol.*, **27**, 135–144.

PEABODY, J. L., WILLIS, M. M., GREGORY, G. A., TOOLEY, W. H. and LUCEY, J. F. (1978) Clinical limitations and advantages of transcutaneous oxygen electrodes. *Acta Anaesth. Scand. Suppl.*, **68**, 76–82.

SEVERINGHAUS, J. W. (1966) Blood gas calculator. *J. Appl. Physiol.*, **21**, 1108.

WINTER, P. M. and SMITH, G. (1972) Oxygen toxicity. *Anaesthesiology*, **37**, 210–241.

WOOD, E. G. and GERACI, J. E. (1949) Photoelectric determination of arterial oxygen saturation in man. *J. Lab. Clin. Med.*, **34**, 387–401.