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 = 0.907x + 8.592 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 95.82 ± 0.675% (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 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.

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.
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):

\[ S = A - B \frac{a_{650}}{a_{805}} \]

where \( a_{650} \) and \( a_{805} \) 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.

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

\[ I = I_0 F_T 10^{-a'd} 10^{-a'l} \]

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, \( a \) and \( a' \) is the quantity of blood that is present at the end of the outflow phase and its absorption coefficient, \( I \) and \( a \) 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

\[ E_{DC+AC} = AI = AI_0 \gamma F_T 10^{-a'd} 10^{-a'l} \]

where \( A \) and \( \gamma \) are constants specific to the photoelectric element.

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

\[ E_{DC} = AI_0 \gamma F_T 10^{-a'd} \]

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

\[ Y = \log\left(\frac{E_{DC+AC}}{E_{DC}}\right) = -a'\gamma l \]

The \( Y \)'s at the wavelengths of 650 and 805 nm (\( Y_{650} \) and \( Y_{805} \), respectively) are calculated as follows:

\[ Y_{650} = -a_{650} \gamma l \]
\[ Y_{805} = -a_{805} \gamma l \]

Therefore

\[ a_{650}/a_{805} = Y_{650}/Y_{805} \]

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

\[ S = A - B \frac{Y_{650}}{Y_{805}} \]

3 Description of the instrument

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