Pulse Oximetry

It is important to estimate tissue oxygenation levels because they reflect the function of several physiological processes forming the links of the oxygen transport chain, e.g., gas exchange in the lung, blood circulation at various levels in the circulatory system, gas exchange at the cellular level, etc. The earlier techniques for blood partial oxygen pressure (pO_2) determination were via blood samples from peripheral arteries followed by measurements in laboratory blood gas analyzers.

Oxygen is transported from the lungs to each cell in the tissue volume via two different routes. About 98% is chemically bound to the hemoglobin molecule in the erythrocyte as oxihemoglobin (HbO_2). The additional 2% is physically dissolved in blood plasma. There is a nonlinear relation between the partial pressure of oxygen and the amount of oxygen in HbO_2. The curves are sigmoid shaped as shown in (Fig. 1)
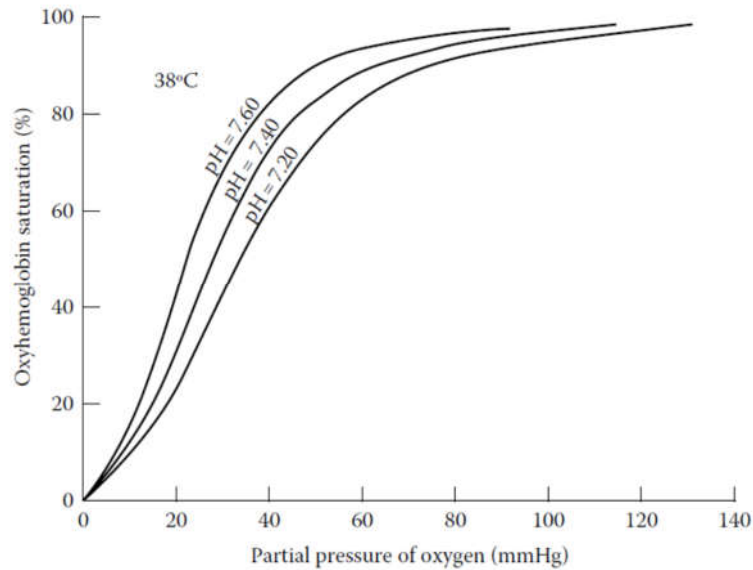

Fig. 1.

As can be seen from the shape of this curve, pO_2 is a sensitive indicator of the blood oxygen level in the upper, right-hand part of the curve, and SO_2 is a more sensitive indicator in the left, steeper part of the curve below 80% saturation. Under normal conditions the pO_2 of arterial blood is about 100 mmHg. The corresponding SO_2 is about 98%.

The Basis of Oximetry

Light absorbance of whole blood varies strongly with the wavelength used and also with the level of oxygenation. Oximetry is based on the differences in the optical transmission spectra between oxygenated and deoxygenated hemoglobin in the visible and near infrared parts of the spectrum. The differences are illustrated by Fig. 2 given below.
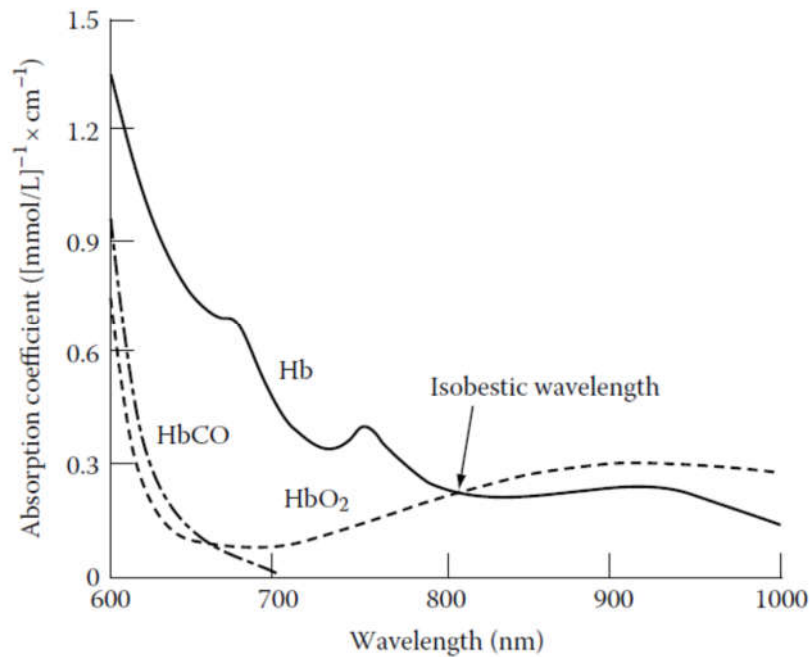
Fig. 2

The two spectra cross at a wavelength of 805 nm. This point is called the **isosbestic point**. At this point the absorption is independent of the oxygenation level of the blood. The point is often used as a reference. The largest difference between the two curves can be found around 650–660 nm. A solution of hemoglobin can be characterized by the degree to which it absorbs light. Beer–Lambert's law can be written as the relation between the incident and transmitted light intensity levels for a fixed geometry

$$\frac{I_t}{I_i} = e^{-acd}$$

where

I_t is transmitted light intensity

I_i is incident light intensity

a is absorption coefficient

c is the concentration of absorbing material

d is length of the optical path

Beer–Lambert's law is often written as an expression for optical density OD by

$$OD = \ln\left[\frac{I_i}{I_t}\right] = a.c.d$$

where OD is the optical density of the blood. If the optical density is determined at two wavelengths (usually ≈660 and 805 or 940 nm) the oxygen saturation SO_2 level can be calculated from the equation,

$$SO_2 = A - B \cdot \frac{OD_1}{OD_2}$$

where

    A and B are empirically determined constants
    OD_1 and OD_2 are the optical densities at two wavelengths

Pulse Oximeters

The Japanese scientist Aoyagi was the first to suggest a different approach to saturation measurements (Aoyagi et al. 1974). He suggested that the optical absorption differences seen at every heart beat are caused by an influx of arterial blood only. Therefore, the pulsatile component in tissue absorption spectra reflects the absorption of the arterial blood selectively. Differentiating light by time, steady components can be removed, then the contribution of arterial blood can be extracted.
Although rigorous derivation of oxygen saturation from optical densities is difficult, a simplified model where Beer Lambert's law is valid can be analyzed as follows (Öberg 2004).

Applying the eqn given below, optical densities,
OD_1 and OD_2, for λ_1 and λ_2, can be expressed by absorption coefficients, a, concentrations, c,
and path length, d, for each wavelength, as

$$OD_1 = a_{o1} \cdot c_o \cdot d + a_{r1} \cdot c_r \cdot d + a_{x1} \cdot c_x \cdot d_x$$

$$OD_2 = a_{o2} \cdot c_o \cdot d + a_{r2} \cdot c_r \cdot d + a_{x2} \cdot c_x \cdot d_x$$

where

suffixes 1 and 2 correspond to wavelength λ_1 and λ_2
o and r denote oxygenated and reduced hemoglobin
x denotes tissue outside the blood vessel

The arterial pulsation can be considered as the change in arterial diameter that corresponds to the change in optical path length, d, while d_x remains unchanged. The changes in optical densities are given as

$$\Delta OD_1 = a_{o1} \cdot c_o \cdot \Delta d + a_{r1} \cdot c_r \cdot \Delta d$$

$$\Delta OD_2 = a_{o2} \cdot c_o \cdot \Delta d + a_{r2} \cdot c_r \cdot \Delta d$$

Then the ratio, R, of optical densities in two wavelength can be obtained as

$$R = \frac{\Delta OD_1}{\Delta OD_2} = \frac{a_{o1}c_o + a_{r1}c_r}{a_{o2}c_o + a_{r2}c_r}$$

On the other hand, oxygen saturation, S, can be expressed as

$$S = \frac{c_o}{c_o + c_r}$$

Hence,

$$S = \frac{(a_{r1} - a_{r2})R}{(a_{r1} - a_{o1}) - (a_{r2} - a_{o2})R}$$

In this equation, R can be measured optically, and all other coefficients are material properties; thus, oxygen saturation, S, can be estimated in principle. Although, this formula does not estimate perfectly, similar empirical formulas can be used in most clinical situations.

Fig. 3 given below shows a block diagram by which the computations can be performed. LEDs of two wavelengths are driven alternatively, transmitted lights are detected by a common detector, taking logarithm, pulsatile components are extracted, and by applying an adequate approximation formula S is obtained. Usually 660 nm is used as one of the wavelengths and 940 nm (or 805 nm, the isosbestic point) is utilized for the second wavelength. The standard pulse oximetry probe consists of red and infrared LEDs and a photodetector. Pulse oximetry signals can be recorded on most parts of the human skin. Fingertips, earlobes, and toes are the most frequently used areas for pulse oximetry measurements but all the areas of the skin give good signals.
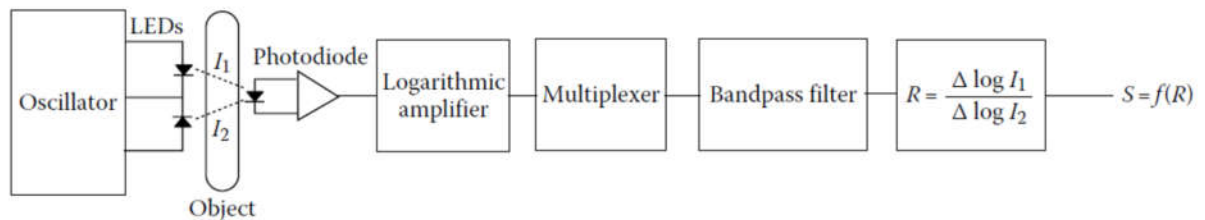

Fig. 3

Pulse oximeters can be of two types: (a) transmission type and (b) reflection type. The topologies are shown in the figure given below (Fig. 4).
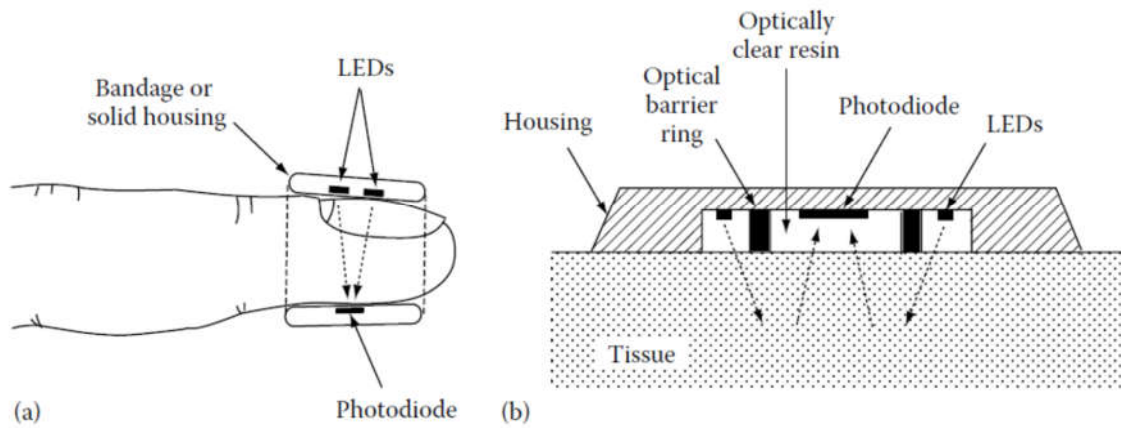
Fig. 4

Logarithmic Amplifier

A log amp must satisfy a transfer function of the form

$V_{OUT} = V_Y \log(V_{IN}/V_X)$ (as shown in Fig. 5)

The constant, V_Y, has the dimensions of voltage, because the output is a voltage.
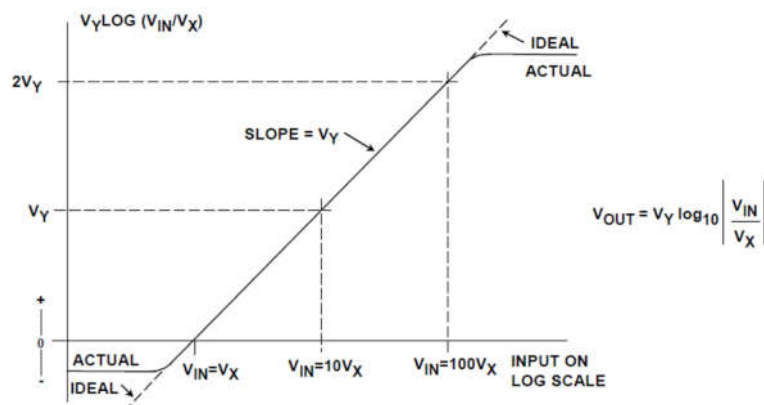

Fig. 5

The voltage across a silicon diode is proportional to the logarithm of the current through it. If a diode is placed in the feedback path of an inverting op-amp, the output voltage will be proportional to the log of the input current as shown in figure given below (Fig. 6). I_o is the saturation current.

$$V = \frac{kT}{q} \ln\left(\frac{I}{I_o}\right)$$

if $I \gg I_o$

$$E_o = \frac{kT}{q} \ln\left(\frac{I}{I_o}\right) \cong 0.06 \log \frac{V_{IN}}{R_{IN} I_o}$$
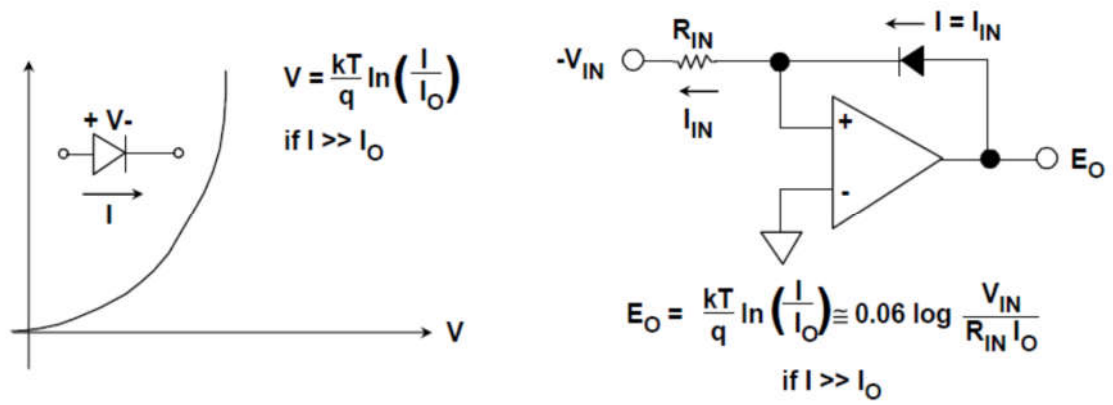
if $I \gg I_o$

Fig. 6

In practice, the dynamic range of this configuration is limited to 40-60 dB because of non-ideal diode characteristic, but if the diode is replaced with a transistor as shown in the next figure (Fig. 7), the dynamic range can be extended to 120 dB or more. (I_{ES} is the saturation current)
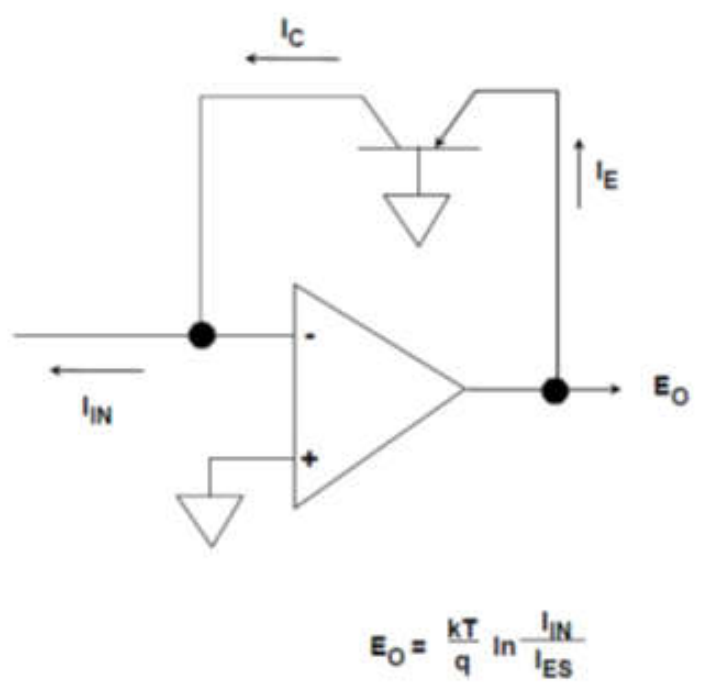
$$E_o = \frac{kT}{q} \ln \frac{I_{IN}}{I_{ES}}$$

Fig. 7