Chapter 31

PULSE OXIMETERS

OBJECTIVES

- State Lambert Beer's law.
- Define S_aO_2, S_pO_2 S_vO_2, fractional oxygen saturation, and functional oxygen saturation.
- State the clinical applications of pulse oximetry.
- Explain the principles of operation of pulse oximeters.
- Describe the construction of a typical pulse oximeter sensor.
- Sketch a typical block diagram of a pulse oximeter and explain the functions of each block.
- Discuss factors affecting signal quality and accuracy of pulse oximeters.
- Differentiate between the clinical application of oxygen analyzers and pulse oximeters.

CHAPTER CONTENTS

INTRODUCTION

One of the main functions of the cardiopulmonary system is to deliver oxygen and remove carbon dioxide to and from the cells. Hypoxia is a general term describing the condition of lack of oxygen in the system. Acute hypoxia produces impaired judgment and motor incoordination. When hypoxia is long standing, the symptoms consist of fatigue, drowsiness, inattentiveness, and delayed reaction time. More severe hypoxia can affect brain function and lead to death.

Until the early 1980s, blood oxygen saturation levels were measured by drawing arterial blood samples from the patient and performing in vitro analysis using laboratory co oximeters (a multiwavelength spectrophotometer). Pulse oximeters were developed in the early 1980s, providing a real time, continuous, and noninvasive means to monitor the changing level of arterial blood oxygenation in patients; and allowing clinical intervention before the occurrence of significant hypoxia. In 1986, pulse oximeters were endorsed by the American Society of Anesthesiologists as a standard of care for use whenever anesthesia is performed. Since then, pulse oximeters have become the preferred method for measuring arterial oxygen saturation and are used in most areas of hospitals.

DEFINITION OF PERCENTAGE OXYGEN SATURATION IN BLOOD

The primary function of red blood cells is to transport oxygen from lungs to tissue. This function is carried out by hemoglobin. When blood is circulated into the lungs, oxygen is attached to hemoglobin, forming oxygenated hemoglobin. Under normal conditions, hemoglobin in blood becomes almost fully saturated with oxygen before leaving the lungs. When blood is in the capillaries, oxygen is released from the oxyhemoglobin and delivered to the cells. The hemoglobin becomes deoxyhemoglobin. In studying oxygen transport in blood, the terms $\%S_aO_2$, $\%S_pO_2$, and $\%S_vO_2$ are commonlyused. Here are their definitions:

- Percent oxygen saturation of hemoglobin in arterial blood ($\%S_a0_2$) is the percentage of hemoglobin in arterial blood that is bound with oxygen; it is determined by analyzing an arterial blood sample with a cooximeter.
- Percent oxygen saturation of hemoglobin in venous blood ($\%S_v0_2$) isPercent oxygen saturation of hemoglobin in venous blood ($\%S_v0_2$) is the percentage of hemoglobin in venous blood that is bound with oxygen; it is usually determined from a blood sample taken from or measured

in the pulmonary artery.

- Percent oxygen saturation of hemoglobin in arterial blood ($\%S_pO_2$) is• Percent oxygen saturation of hemoglobin in arterial blood ($\%S_pO_2$) is determined by a pulse oximeter (instead of from a blood sample by a co oximeter).

In addition to oxyhemoglobin and deoxyhemoglobin, there are two other forms of hemoglobin. Carboxyhemoglobin is hemoglobin bound with carbon monoxide. Methemoglobin is the oxidized form of hemoglobin. Methemoglobin is incapable of binding with oxygen. A high percentage of carboxyhemoglobin or methemoglobin compromises the oxygen carrying capacity of blood as there is less hemoglobin available to bind with oxygen.

Table 31 1 shows the normal values of $\%S_aO_2$ and $\%S_pO_2$ with the corresponding blood gas values of normal adults and neonates.

Table 31-1.
Typical Values of Blood Oxygen Level

Adult	$\%S_aO_2$	96 to 98%	P_aO_2	85 to 100 mmHg	P_aCO_2	38 to 42 mmHg
	$\%S_vO_2$	70-75%	P_vO_2	35 to 40 mmHg	P_vCO_2	41 to 51 mmHg
Neonates	$\%S_aO_2$	94%	P_aO_2	63 to 87 mmHg	P_aCO_2	31 to 35 mmHg

PRINCIPLES OF OPERATIONPRINCIPLES OF OPERATION

The principle of pulse oximetry is based on Lambert Beer's law with differential light absorption of two wavelengths. The wavelengths of the most commonly used sources are red (660 nm) and the infrared (940 nm).

Lambert Beer's law states that for a substance of concentration C in afluid, the absorbance (A) of light due to the substance in the fluid, which isdefined as the natural logarithm of the ratio of incident light intensity (Io) to the transmitted intensity (I) is equal to the product of the absorptivity (a'), th substance's concentration (C) in the fluid and the distance of the optical path length (d). figure 31 1 illustrates this concept.

For a mixture of two substances X and Yin the fluid, the total absorbance*A* is given by the sum of the absorbance due the substance X and the substance Malone, or:

$$A = A_x + A_y.$$

Two equations are used by pulse oximeter device manufacturers to calculate oxygen saturation in blood. They are the fractional oxygen saturation and the functional oxygen saturation equations.

(i) Fractional oxygen saturation ($\%\ O_2Hb$) O2Hb) is equal to the ratio of the

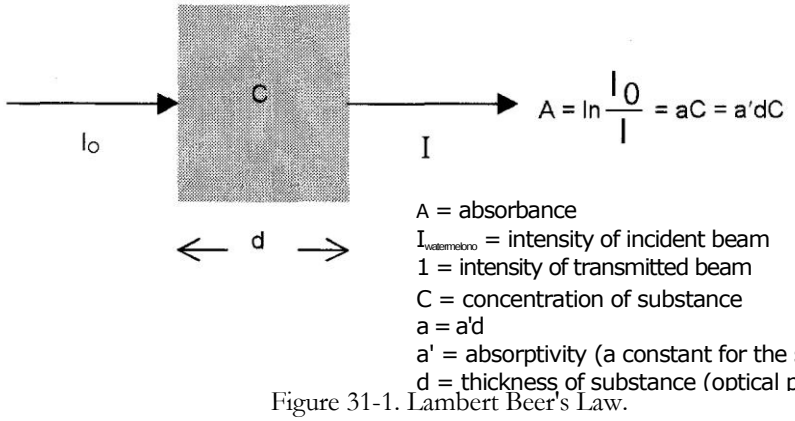

Figure 31-1. Lambert Beer's Law.

concentration of oxyhemoglobin in blood to the sum of concentrations of all types of hemoglobin in blood.

$$\%O_2Hb = \frac{C_{O_2Hb}}{C_{HHb} + C_{O_2Hb} + C_{COHb} + C_{metHb}} \times 100\%, \qquad (1)$$

where:

C_{02Hb} = the concentration of oxygenated hemoglobin in arterial blood,
C_{HHb} = the concentration of deoxygenated hemoglobin in arterial blood,
C_{COHb} = the concentration of carboxyhemoglobin in arterial blood, and
C_{metHb} = the concentration of methemoglobin in arterial blood.

(ii) Functional oxygen saturation ($\%S_aO_2$) is equal to the ratio of the concentration of oxyhemoglobin in blood to the sum of the functional hemoglobin concentrations. That is, the concentrations of the oxyhemoglobin and the deoxyhemoglobin, which are responsible for the oxygen transport.

$$\%S_aO_2 = \frac{C_{O_2Hb}}{C_{HHb} + C_{O_2Hb}} \times 100\%. \qquad (2)$$

It is obvious from the preceding equations that the functional value is higher than the fractional value for the same blood sample. For most patients, the concentration of carboxyhemoglobin as well as that of the methemoglobin is negligible. In a healthy individual, the difference between $\%S_aO_2$ and $\%0_2H_b$ is less than 3%.

Figure 31 2 shows the absorption spectrum of oxyhemoglobin (O_2H_b) and deoxyhemoglobin (HHb). To measure the $\%S_aO_2$ (or $\%0_20_b$) in a blood sample, two light sources of wavelengths λ 1 and λ2 are used. In the bloodsample, two light sources of wavelengths λ 1 and λ2 are used. In the bloodsample, let:

Co be the concentration of oxyhemoglobin (0_2H_b) in blood, and

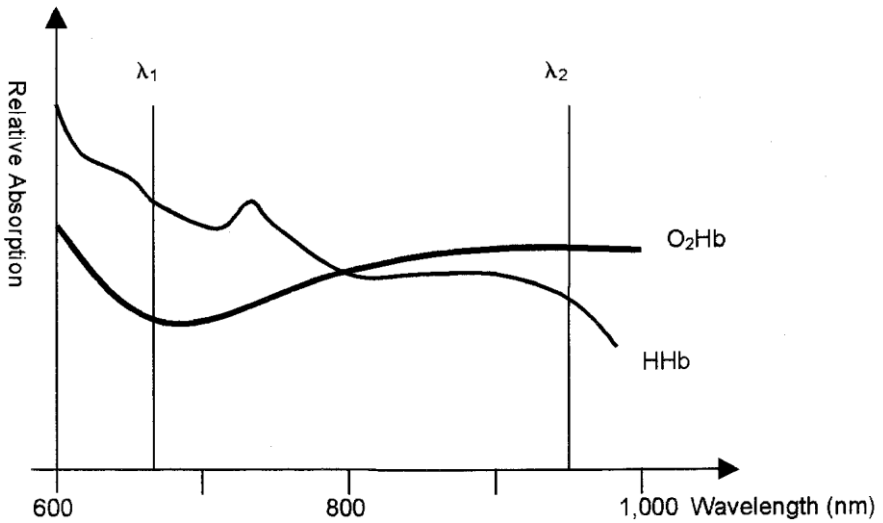

Figure 31 2. Absorption Characteristics of Oxy and Deoxyhemoglobin.

Cd be the concentration of of deoxyhemoglobin (HHb).

At wavelength λ 1, using Lambert Beer's law:At wavelength λ 1, using Lambert Beer's law:

$$A_1 = A_{10} + A_{1d} = {}_{a10}C_o + {}_{a1d}C_d, \qquad (3)$$

where Aι = the total absorption due to wavelength λ1where Aι = the total absorption due to wavelength λ1

A10 = the absorption of oxyhemoglobin due to wavelength λ 1

Aιd = the absorption of deoxyhemoglobin due to wavelength λ1

a10 = the product of the optical path length and the absorptivity of oxyhemoglobin due to wavelength λ1,andmoglobin due to wavelength λ1,and

a1d = the product of the optical path length and the absorptivity of deoxyhemoglobin due to wavelength λ 1oglobin due to wavelength λ 1

At wavelength λ2, using Lambert Beer's law:At wavelength λ2, using Lambert Beer's law:

$$A_2 = A_{20} + A_{2d} = {}_{a2o}C_o + {}_{a2d}C_d. \qquad (4)$$

One can solve equations (1) and (2) for C_o and C_d if A_1, A_2, a_{10}, a_{1d}, a_{20}, a_{2d} are known. Knowing Co and Ad, the oxygen saturation can be computed.Using the functional oxygen saturation equation (Equation 2):

$$\%S_aO_2 = \frac{C_o}{C_o + C_d} \times 100\%$$

$$= \frac{1}{1 + \frac{C_d}{C_o}} \times 100\%.$$

In practice, the light beams travel through the tissue and are absorbed not only by the hemoglobin but also by other tissues (such as bone, muscle) in the light path. In addition, as the diameters of the capillaries are pulsating according to the blood pressure, the optical path length is not a constant. Therefore, a10, a1d, a2d, and a2d, which are the product of the absorptivity and optical path length are not exactly constant values and hence C_o and C_d cannot be computed analytically.

Figure 31 3 shows the absorption waveform measured by the light sensor in a pulse oximeter probe. A red beam (λ1 = 660 nm) and an infraredsor in a pulse oximeter probe. A red beam (λ1 = 660 nm) and an infrared (λ2 = 940 nm) beam are commonly used. The solid and dotted waveformsare results of the absorption characteristics of each of the beams.

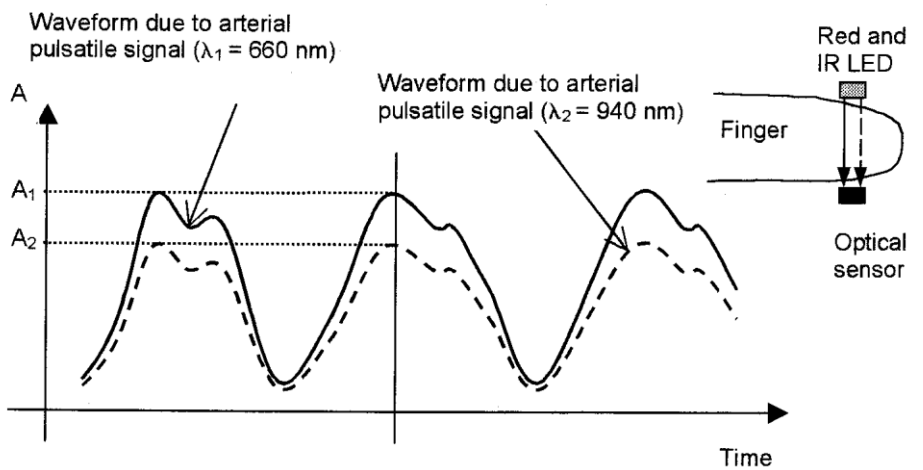

Figure 31–3. Absorption Signal from Pulse Oximeter Finger Probe.

Most pulse oximeter manufacturers derive the $\%S_aO_2$ values from the optical intensity ratio (r) of the transmitted intensity of the red (I_{rd}) and infrared beam (I_{ir}) measured by the sensors in the probe.

$$r = \frac{I_{rd}}{I_{ir}}. \qquad (5)$$

In most cases, an empirical equation or a lookup table between r and the $\%S_aO_2$ values is established so the $\%S_aO_2$ value can be determined from the measured I_{rd} and I_{ir}. This correlation between r and the $\%S_aO_2$ is verified statistically by simultaneously reading the pulse oximeter output and drawing n arterial blood sample from the patient and analyzing the sample by a coximeter. Pulse oximeters are calibrated using arterial blood samples (blood Oximeter) using either the $\%O_2H_b$ (fractional) or $\%S_aO_2$ (functional) equations.

PULSE OXIMETER SENSOR PROBES

Many different types of sensor probes are used in pulse oximetry. A typical probe consists of two light emitting diodes (LEDs), one emitting red light and the other emitting infrared. These LEDs are pulsed alternately to send a beam of light through the underlying tissues (see the top right figure in Figure 31 3). A photodetector in the probe on the other side of the tissue picks up the transmitted light signal and sends it to the processing circuits. Probes can be classified as reflectance or transmittance, disposable or reusable, or by their sensing locations. A disposable probe is one that will be discarded after being used on a single patient (however, some sites reuse some probes that are labeled "single use" for cost saving). The LEDs and the photodetector are mounted on each end of a flexible strip. The strip is applied on and often taped over the tissue (Figure 31 4). A reusable probe usually has a more robust and rigid cover to protect the LEDs and the detector. A transmitting probe has the LEDs on one side and the detector on the other side of the capillary bed. The light is transmitted through the capillary bed and tissues. On the other hand, in a reflecting probe, the detector is placed on the same side as the LEDs. As the light penetrates the tissue, some is absorbed and some is reflected back to the surface. The detector picks up the reflected signal and sends it to the processor. Pulse oximeter probes in theory can be placed over any part of the body with capillaries. However, common sites for transmitting probes are the index finger and the earlobe. For infants, probes are often taped to the big toe. Transmitting probes are usually placed on the forehead of the patient.

FUNCTIONAL BLOCK DIAGRAM

Figure 31 5 shows a typical functional block diagram of a pulse oximeter. It consists of:

- A probe consisting of a red LED, an infrared LED, and a photodetector.
- A timing control circuit to sequence the LEDs and synchronize them with the photodetector. There are three phases in one timing cycle: Red "on" and IR "off," Red "off" and IR "on," and both LEDs "off." The latter is to measure the dark signal to eliminate the effects of the ambient light.
- Analog and digital electronics to amplify and process the signal.
- A processor to compute the transmitted red and infrared light intensity ratio and match the $\%S_aO_2$ from the lookup table. It can also derive

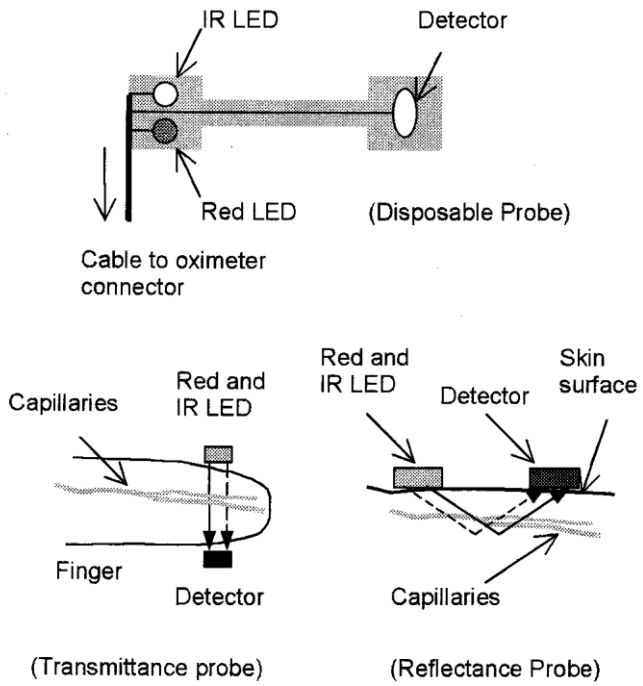

Figure 31 4. Pulse Oximeter Probes.

the heart rate from the pulsating waveform and compares the measured values (heart rate, $\%S_aO_2$) to the alarm settings.

- A display to show the $\%S_aO_2$ values, the alarm limits, and the heart rate. A plethysmograph showing the detected signal strength is often displayed to provide the user an idea of the signal to noise information of the measurement. A strong signal level indicates that the measured value is reliable. A plethysmograph can be a waveform similar to the absorption waveform shown in Figure 31 3 or simply a one column bar graph proportional to the detected signal strength.

ERRORS IN PULSE OXIMETRY

Although we can empirically establish an accurate relationship under ideal situations between the optical intensity ratio *(r)* and $\%S_aO_2$, in the presence of patient motion or other interference, the optical densities will inevitably include noise components (N). Therefore, in the presence of noise, inevitably include noise components (N). Therefore, in the presence of noise, the measured beam intensity I = $S + N$ where S is the desired signal and N is the noise. The optical intensity ratio (equation 5) is now rewritten as

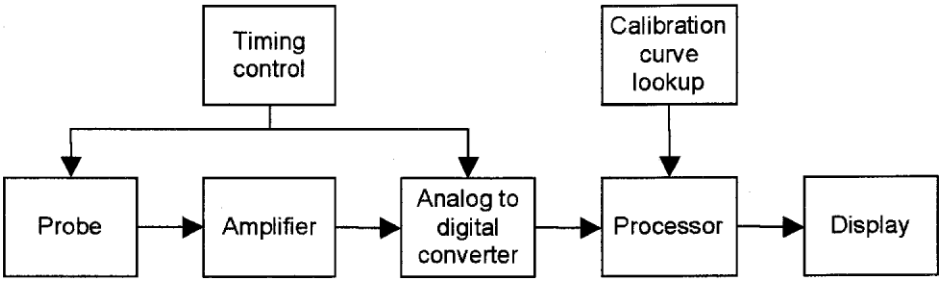

Figure 31 5. Block diagram of Pulse Oximeter.

$$r = \frac{S_{rd} + N_{rd}}{S_{ir} + N_{ir}}. \qquad (6)$$

A well observed source of noise is the change in light absorption caused by patient motion. The movement changes the optical path length of blood vessels and tissues. In a poor signal to noise ratio situation, the noise level becomes significant in the optical intensity ratio. This will increase the error in the derived $\%S_aO_2$. $\%S_aO_2$. If the noise *(Λ* component is much larger than the signal (S), i.e. N>> *S,* the optical intensity ratio in equation (6) then becomes

$$r = \frac{N_{rd}}{N_{ir}}.$$

Under such conditions, if the noise level in the red and IR regions are similar (i.e., *Nrd = Nir),* the optical intensity ratio r will approach unity.

For most systems with a good signal to noise ratio, r= 1.0 corresponds to a $\%S_aO_2$ of about 82%. For that reason, a pulse oximeter working under noisy conditions will tend to report a lower oxygen saturation reading. To maximize the signal to noise ratio, the transmitted beam intensity should be measured during the systolic region of the blood pressure cycle. There have been some reported successes by manufacturers using special digital signal processing techniques such as adaptive filtering or signal extraction to minimize the effect of noise in pulse oximetry.

In summary, errors in pulse oximetry measurement are due to the following causes:

- Poor perfusion patient suffering from poor perfusion usually has lower than normal blood pressure. A lack of blood in the capillaries lower than normal blood pressure. A lack of blood in the capillaries will decrease the signal to noise ratio and therefore increase the error of the measurement.
- Excessive signal attenuation Patients with dark skin pigment or too thick tissue (e.g., skin) at the measurement site will decrease the signal penetration (decrease the detector signal level) and increase measurement

error.

- External interference EMI and ambient light can introduce errors inExternal interference EMI and ambient light can introduce errors in measurement. There were reported incidents that flashing light and fluorescent light sources were misinterpreted by machines as pulsating red or IR signals. To avoid external light interference, pulse oximeter probes are usually designed with a cover to block external light from reaching the sensor.

- Motion Motion will cause changes in the optical path length, which will produce measurement errors.

- Substances in blood Some substances in the bloodstream may affect the absorption of the light sources. A high level of dyshemoglobin in carbon monoxide poisoning, low hematocrit counts of an anemic patient, and artificial dyes in a patient's blood can all affect the accuracy of the measurement.

DIFFERENCES BETWEEN PULSE OXIMETERS AND OXYGEN ANALYZERS

Oxygen analyzers and pulse oximeters are the two devices commonly used today to monitor a patient's oxygen level in the clinical environment. An oxygen analyzer measures the percentage of oxygen gas in a gas mixture such as the inspired air of a patient. Oxygen analyzers are usually attached to the patient breathing circuit. A pulse oximeter measures the oxygen content in the patient's blood. Measuring oxygen saturation level in blood can detect hypoxia even before other signs such as cyanosis or hyperventilation are observed. Table 31 2 summarizes the main differences between the twodevices.

Table 31 2.
Oxygen Analyzer and Pulse Oximeter Comparison.

	Oxygen Analyzer	*Pulse Oximeter*
Principle of operation	Electrochemical transducer	Lambert Beer's law
Parameter sensed	Partial pressure of 0_2 in airway	Oxygen saturation in blood
Hypoxia detection	Detects oxygen deficiency in inhaled air	Detects insufficient oxygen in blood stream

Both devices are often used together to detect insufficient oxygen to the patient. They provide complementary protection against hypoxia. For example

in anesthesia, an oxygen analyzer is connected to the inspiratory limb of the patient breathing circuit to sound an alarm on low oxygen level in the patient's inspired gas. A pulse oximeter is connected to the patient (e.g., using a finger probe) to detect the actual level of oxygen in the patient's bloodstream.