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## 1 What is a pulse oximeter?

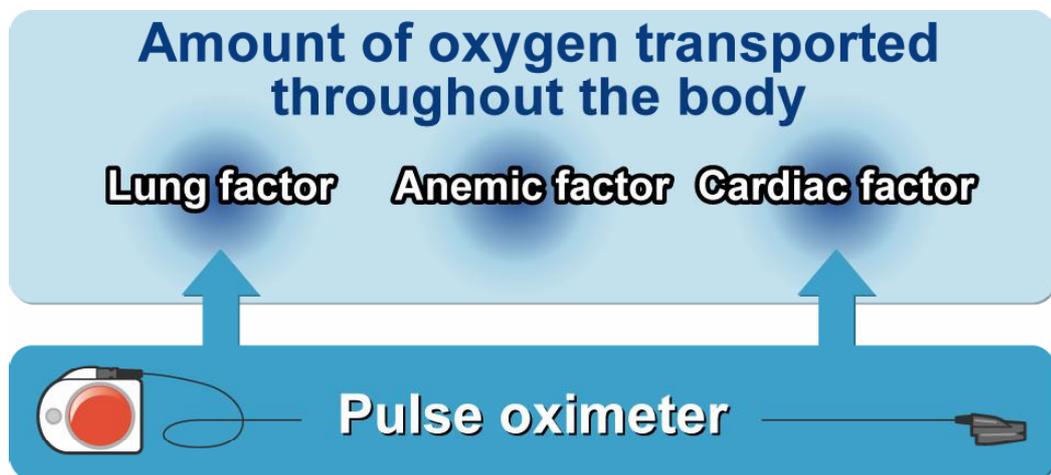
Oxygen binds to hemoglobin in red blood cells when moving through the lungs. It is transported throughout the body as arterial blood. A pulse oximeter uses two frequencies of light (red and infrared) to determine the percentage (%) of hemoglobin in the blood that is saturated with oxygen. The percentage is called blood oxygen saturation, or SpO<sub>2</sub>. A pulse oximeter also measures and displays the pulse rate at the same time it measures the SpO<sub>2</sub> level.

## 2 What can be learned by monitoring blood oxygen saturation?

Oxygen in the atmosphere is brought into the lungs by breathing. Each lung contains nearly 300 million alveoli which are surrounded by blood capillaries. Since alveolar walls and capillary walls are very thin, oxygen passing into the alveoli immediately transfers into the blood capillaries. (Usually in adults, the transfer would take about 0.25 seconds while resting.) A large proportion of the oxygen diffusing into the blood binds to hemoglobin in the red blood cells, while a part of the oxygen dissolves in the blood plasma. Blood enriched with oxygen (arterial blood) flows through pulmonary veins, then into the left atrium and left ventricle, and finally circulates throughout the body's organs and their cells. The amount of oxygen transported around the body is determined mainly by the degree to which hemoglobin binds to oxygen (lung factor), hemoglobin concentration (anemic factor), and cardiac output (cardiac factor).

Oxygen saturation is an indicator of oxygen transport in the body, and indicates if sufficient oxygen is being supplied to the body, especially to the lungs.

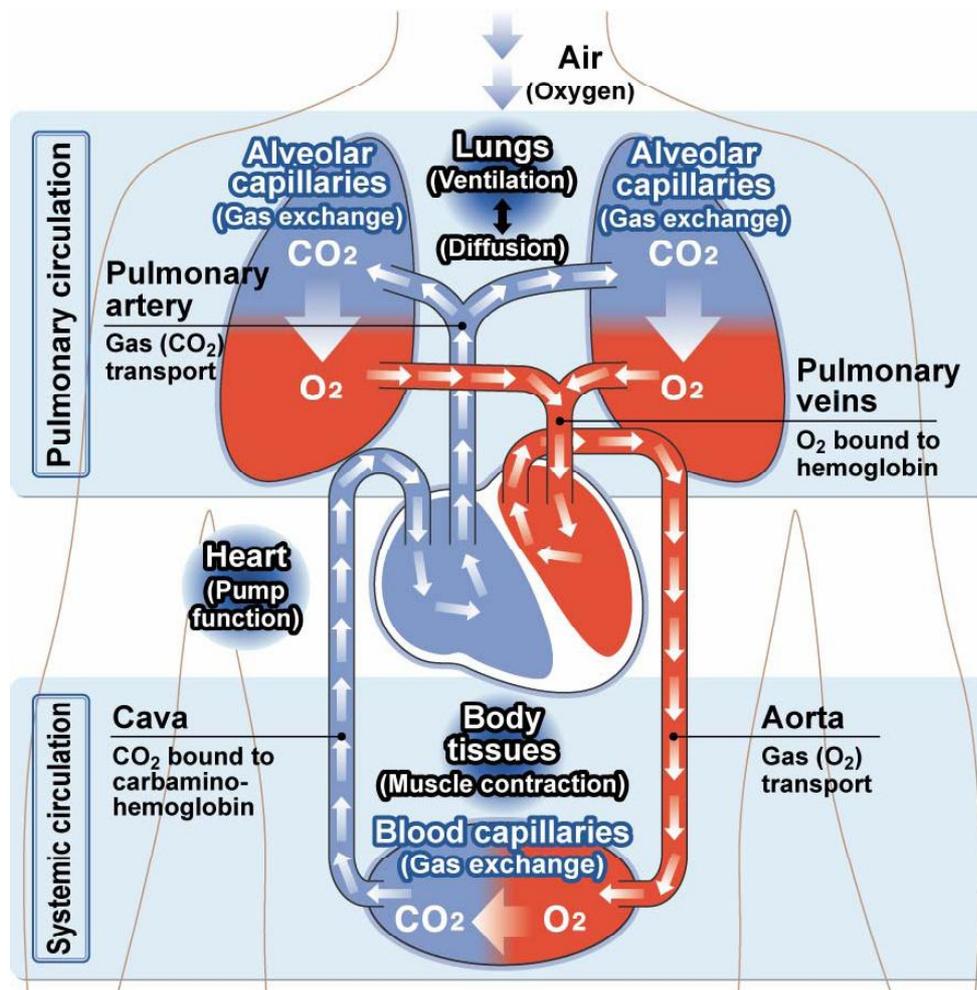
The pulse oximeter can also measure pulse rate. The volume of blood being pumped by the heart per minute is called the cardiac output. The frequency of pumping during one minute is called the pulse rate. These cardiac function indicators can be determined by the pulse oximeter.



### 3 How does oxygen move around the body?

We need oxygen to sustain our lives. Oxygen in the atmosphere is brought into the lungs by breathing, and into the blood via lung capillaries. Then it is transported throughout the body by the blood.

- Oxygen is inhaled into the lungs, and carbon (carbon dioxide) is exhaled from the lungs to the air. This process is called ventilation.
- Inhaled air flows into the upper airway, then into the peripheral airways, and is finally distributed into the lungs. This process is called distribution.



The lungs consist of tissues called alveoli. Oxygen is absorbed from the alveoli, then into the lung capillaries via alveolar membranes, while carbon dioxide moves from the lung capillaries to the alveoli. This process is called diffusion.

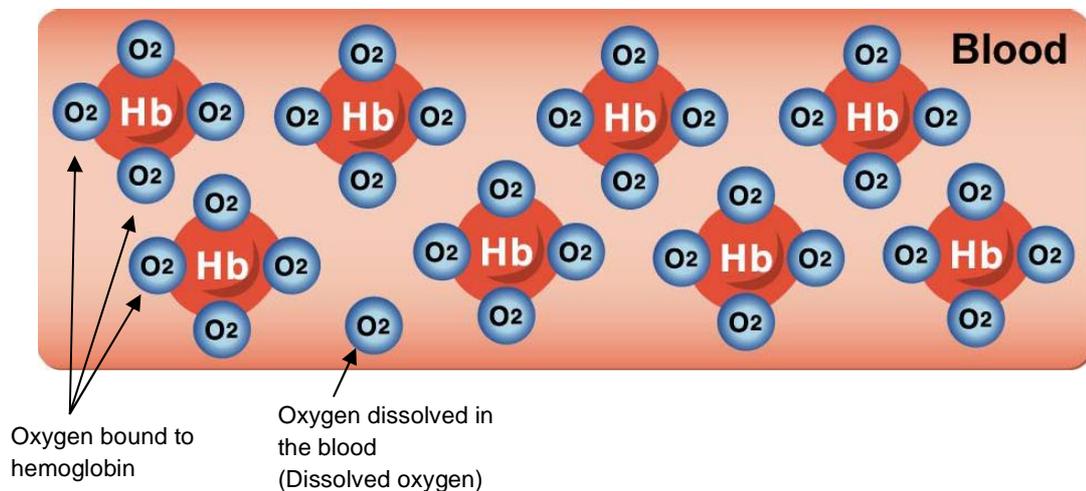
## 4

## How does oxygen get into the blood?

One of the main functions of blood is to receive oxygen from the lungs and transport it into the body's tissues. At the same time, blood receives carbon dioxide from the tissues, and brings it back to the lungs.

The amount of gas dissolved in a liquid (blood, in this case) is proportional to the pressure (partial pressure) of the gas. In addition, each gas has a different solubility. Only about 0.3 ml of gaseous oxygen dissolves in 100 ml blood per mmHg (pressure). This amount is only 1/20 of carbon dioxide solubility. This suggests that a human could not get sufficient oxygen if solubility were the only way to get oxygen in the blood. For this reason, hemoglobin (Hb) has an important role as a carrier of oxygen.

One molecule of hemoglobin can bind to 4 molecules of oxygen, and 1 g of hemoglobin can bind to 1.39 ml of oxygen. Since 100 ml of blood contain about 15 g of hemoglobin, the hemoglobin contained in 100 ml of blood can bind to 20.4 ml of oxygen.



Amount of oxygen contained in 100 ml of blood (20.7 ml) =  
Dissolved oxygen (0.3 ml) + Hb-bound oxygen (20.4 ml)

## 5

## What is oxygen saturation?

Hemoglobin bound to oxygen is called oxygenated hemoglobin (HbO<sub>2</sub>). Hemoglobin not bound to oxygen is called deoxygenated hemoglobin (Hb).

The oxygen saturation is the ratio of the oxygenated hemoglobin to the hemoglobin in the blood, as defined by the following equation.

$$\text{Oxygen saturation} = \frac{C(\text{HbO}_2)}{C(\text{HbO}_2) + C(\text{Hb})} \times 100 (\%)$$

C (Hb) = Concentration of deoxygenated hemoglobin

C (HbO<sub>2</sub>) = Concentration of oxygenated hemoglobin

Since each hemoglobin molecule can bind to 4 molecules of oxygen, it may bind with 1 to 4 molecules of oxygen. However, hemoglobin is stable only when bound to 4 molecules of oxygen or when not bound to any oxygen. It is very unstable when bound to 1 to 3 molecules of oxygen. Therefore, as shown in the above figure, hemoglobin exists in the body in the form of deoxygenated hemoglobin (Hb) with no oxygen bound, or as oxygenated hemoglobin with 4 molecules of oxygen. Oxygen saturation can be assessed by SaO<sub>2</sub> or SpO<sub>2</sub>. SaO<sub>2</sub> is oxygen saturation of arterial blood, while SpO<sub>2</sub> is oxygen saturation as detected by the pulse oximeter. They are called arterial blood oxygen saturation and percutaneous oxygen saturation, respectively.

## 6

## Does the ratio of PaO<sub>2</sub> to SpO<sub>2</sub> always remain the same?

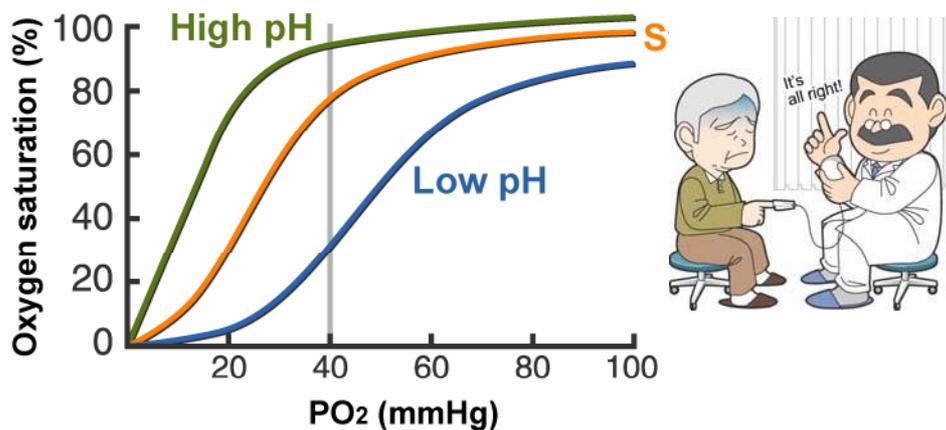
The amount of oxygen dissolved in the blood is proportional to the partial pressure of oxygen. The amount of oxygen bound to hemoglobin will increase as the partial pressure of oxygen increases. The partial pressure of oxygen is expressed as PO<sub>2</sub>, and the partial pressure of arterial blood is expressed as PaO<sub>2</sub>. In contrast, the amount of oxygen bound to hemoglobin does not increase in proportion to the partial pressure of oxygen. The increase may be indicated by an S-shaped curve as shown in the graph below. This is called the oxygen dissociation curve.

The oxygen dissociation curve is called the "standard oxygen dissociation curve" in which the body temperature is 37°C, pH 7.4. The curve may shift to the right or left, depending on patient conditions.

If the body temperature decreases and pH increases, the curve will shift to the left. If the temperature increases and pH decreases, the curve will shift to the right.

In the following graph, the low pH curve shows that when PaO<sub>2</sub> is 80mmHg (Torr), oxygen saturation is 80%.

It may seem that sufficient oxygen cannot be supplied under any circumstances. In fact, the oxygen saturation decreases to 30% when PaO<sub>2</sub> is 40 mmHg (Torr) in the blood capillaries. That is, the oxygen saturation in the tissues is 80% - 30% = 50%. Since the oxygen saturation is 98% - 75% = 23% with standard pH, the oxygen saturation in the blood capillaries is much higher than with standard pH.



### Concerning mmHg and Torr

Standard atmospheric pressure is 760 mmHg. This means atmospheric pressure is the same as that exerted by a 760 mm high column of mercury (Hg).

The first measurement of atmospheric pressure was performed by Torricelli, a student of Galileo Galilei. One mmHg is referred to by the term "Torr" after his name. The unit "mmHg" is the same as "Torr," and one atmospheric pressure is 760 mmHg = 760 Torr. Currently, Torr is generally used when measuring PaO<sub>2</sub>.

## 7 What is the purpose of the pulse oximeter?

Pulse oximeters were first used for vital sign monitoring during operations and anesthesia. Since the device is non-invasive and allows immediate and real time monitoring, its use has expanded to include other purposes such as screening, diagnosis, patient follow-up, and self-monitoring. Examples of how the pulse oximeter is used are shown below.

### 1. Determining the severity of a disease

The severity of a disease can be determined by clinical symptoms including SpO<sub>2</sub>.

## 2. Blood gas analysis

Deciding whether to perform blood gas analysis in order to better understand the patient's condition.

## 3. Deciding on hospitalization of patients with chronic diseases when in acute phase

The need for hospitalization is determined by clinical symptoms including SpO<sub>2</sub>.

## 4. Home oxygen therapy, prescribing oxygen, and educating patients receiving home oxygen therapy

### 1. Home oxygen therapy

Home oxygen therapy (HOT) may be covered by health insurance under the following conditions. Concerning point (1), below, oxygen saturation can be measured by the pulse oximeter, and blood gas analysis in combination with the pulse oximeter is generally used.

#### (1) Profound respiratory failure

For patients in stable condition, with PaO<sub>2</sub> of 55 mmHg or less at rest during inhalation of room air (one atmosphere) or those with PaO<sub>2</sub> of 60 mmHg or less with marked hypoxemia during sleep or exercise.

#### (2) Pulmonary hypertension

#### (3) Chronic heart failure

For patients who have been diagnosed by a physician as having grade III or more of the New York Heart Association (NYHA) classification, with Cheyne-Stokes respiration (CSR) during sleep as well as when the apnea-hypopnea index (frequency of apnea and hypopnea per hour) is greater than 20 episodes per hour as confirmed by polysomnogram.

#### (4) Cyanotic congenital heart disease

### 2. Prescribing oxygen

The amount of oxygen required depends on each patient's condition. The physician should determine the source of oxygen to be used, the appropriate oxygen flow, inhalation method, time of inhalation, and the amount of oxygen to be taken at rest, as well as during exertion and sleep.

### 3. Management of patients receiving HOT

Patients receiving HOT should have checkups at least monthly and education/management training by their physicians, including monitoring of blood oxygen saturation.



In addition, patients receiving long-term HOT should have overnight monitoring of SpO<sub>2</sub> regularly to confirm whether the level of SpO<sub>2</sub> decreases during sleep. Polysomnography should be performed, if necessary, to collect evidence of sleep hypoventilation.

#### 4. Education of patients receiving HOT

Patients, who do not show clear subjective symptoms and have poor compliance with their physician's instructions due to their psychological resistance to HOT, are instructed to carry the pulse oximeter in order to recognize decreased oxygen saturation and enhance their awareness about the importance of HOT.

#### 5. Starting Noninvasive Positive Pressure Ventilation (NPPV) for patients with chronic respiratory failure

For patients with restrictive ventilation disorders (such as late-stage symptoms of pulmonary tuberculosis, or kyphoscoliosis), those in a mild phase of COPD, obesity hypoventilation syndrome, CSR, acute phase of COPD, neuromuscular disorder, etc., SpO<sub>2</sub> is monitored to help determine whether to use NPPV.

#### 6. Assessment and risk management of respiratory rehabilitation and exercise therapy

#### 7. Vital sign monitoring of hospitalized patients

SpO<sub>2</sub> is the fifth most important vital sign after pulse rate, body temperature, blood pressure, and respiration. Even if no respiratory symptoms are observed, the level of SpO<sub>2</sub> should be recorded. If treatments or examinations influence a patient's respiration, their respiratory condition should be followed up as appropriate.

In respiratory and cardiovascular wards, routine SpO<sub>2</sub> monitoring is performed by nurses on each patient during their rounds in the morning, afternoon and evening.



#### 8. Daily management of HOT patients with chronic respiratory failure

A growing number of HOT patients with chronic respiratory failure have used the pulse oximeter for routine monitoring.

## 9. Screening for sleep apnea syndrome

A pulse oximeter with memory function is used to record oxygen saturation (SpO<sub>2</sub>) during sleep to determine the frequency of hypoxemia events (oxygen desaturation index), as well as the duration of desaturation.

## 10. Screening for dysphagia and its monitoring by examination

The pulse oximeter is used as a part of monitoring of patients with dysphagia when they are observed while eating.

## 11. Diagnosis of polycythemia

The oxygen saturation may decrease in patients with pulmonary diseases such as COPD, sleep apnea syndrome, cardiac disorders such as valvulopathy, as well as persons living at high altitudes.

In these cases, the bone marrow is stimulated to produce more red blood cells and consequently polycythemia (secondary polycythemia).

The pulse oximeter may be used to measure SpO<sub>2</sub> and determine causes of polycythemia.

## 12. Monitoring during examinations such as endoscopy

The pulse oximeter is an essential device for bronchoscopy.

Prior to examinations, sedatives are administered. Patient conditions are observed by monitoring changes in heart rate and SpO<sub>2</sub> in order to ensure safe examinations.

The pulse oximeter is often used with photogastroscopy and fibroptic colonoscopy.

# 8

## Where is the pulse oximeter used?

Initially, pulse oximeters gained wide acceptance in hospital operation and anesthesia rooms. Equipment used for patients in acute condition includes stationary pulse oximeters and bioinstrumentation systems which can simultaneously monitor other important vital signs, for example when using an electrocardiogram.

During post-operational recovery or in subacute phases, telemetric, hand-held monitoring units are fixed to the bedside in addition to the stationary pulse oximeter. This equipment is used to warn of sudden deterioration of a patient's condition.

Meanwhile, small portable pulse oximeters are frequently used both in hospitals and for outpatient care.

The following section describes where small, portable pulse oximeters are used.

### 1. Hospitals

Small, portable pulse oximeters are used in hospitals, especially by nurses in respiratory and cardiovascular wards. The main purpose is to monitor the vital signs of hospitalized patients.

SpO<sub>2</sub> is the fifth most important vital sign monitored, after pulse rate, body temperature, blood pressure, and respiration. It is monitored in the morning, afternoon and evening in order to check patient conditions.

## 2. Outpatient

The pulse oximeter is used for screening blood samples, mainly in respiratory departments. Some physicians use the pulse oximeter to monitor SpO<sub>2</sub> of patients who are suspected of having respiratory diseases in order to learn their normal values. They then use the values as reference data if the patient's condition deteriorates.



## 3. Respiratory function tests and rehabilitation in hospitals

The pulse oximeter is used for examination and assessment of respiratory function tests and walking tests. These tests may be conducted by laboratory technicians or physical therapists. The device is also used by physical therapists for risk management during patient rehabilitation to confirm a decrease in SpO<sub>2</sub> and an increase in pulse rate as needed.



## 4. Clinics (Clinical internists)

Hypoxemia involves the respiratory, cardiovascular, and nervous systems. The pulse oximeter is used in the field of respiratory internal medicine and general internal medicine, and can determine the necessity of sending patients to specialist hospitals. It can also make differential diagnoses and analyze the severity of a condition. At the same time, the portable pulse oximeter is an essential device for home-visit medical service.



## 5. Home visit nursing

Most patients receiving home visit nursing service are elderly. Generally they have some respiratory or cardiovascular system difficulties even if respiratory disease is not the main cause of their problems. SpO<sub>2</sub> measurement has been widely used by home visit nurses as a method to quickly assess their patients' respiratory and cardiovascular conditions.

## 6. Eldercare facilities

Pulse oximeter use in eldercare facilities has not yet reached the level of usage by home visit nurses. However, it is expected that the devices will become more widely accepted for vital sign monitoring



of patients in hospitals and daycare facilities, especially during those times (often during the night) when their conditions may deteriorate.

## 7. Other situations

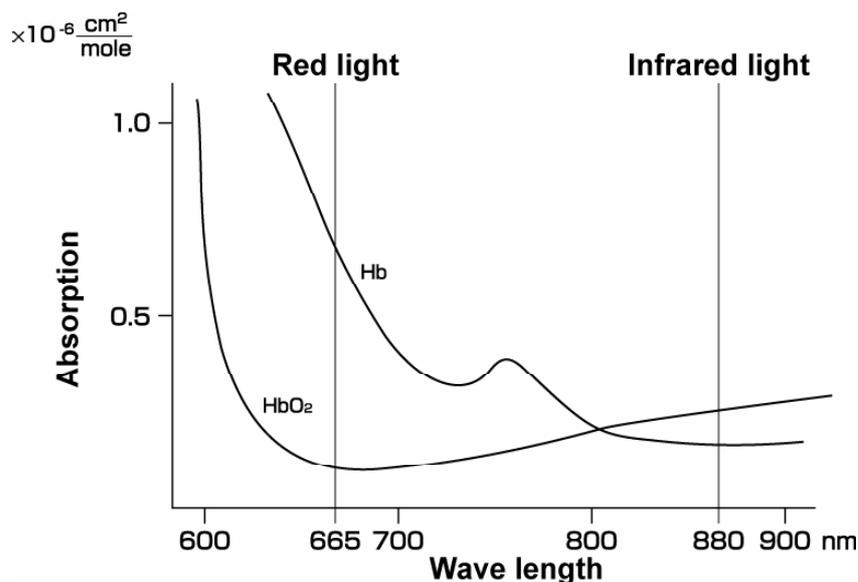
When the air pressure drops, the partial pressure of oxygen in the inhaled air decreases, resulting in a decrease in oxygen saturation.

The pulse oximeter is used to prevent accidents that might occur during flight and high altitude climbing. Patients receiving HOT (home oxygen therapy) who travel by air or participate in mountain climbing events are often equipped with small, portable pulse oximeters, as are many airliners and organizations involved in high-altitude sports and hypoxic training.

## 9 How does the pulse oximeter measure oxygen saturation?

Hemoglobin bound to oxygen is called oxygenated hemoglobin and has a bright red color. Hemoglobin with no oxygen bound to it is called deoxygenated hemoglobin and has a dark red color.

That is why arterial blood is bright red and venous blood is dark red.



The graph above shows spectroscopic and absorptive properties (properties regarding which color is absorbed) of oxygenated hemoglobin (HbO<sub>2</sub>) and deoxygenated hemoglobin (Hb). Oxygenated hemoglobin absorbs more infrared light, while deoxygenated hemoglobin absorbs more red light.

The percentage of oxygenated hemoglobin and deoxygenated hemoglobin is determined by measuring the ratio of infrared and red light detected by the pulse oximeter.

The pulse oximeter emits red (R) and infrared (IR) LED light that passes through the body, receives data from a photodetector, and calculates the oxygen saturation by determining the ratio of the two waveforms.

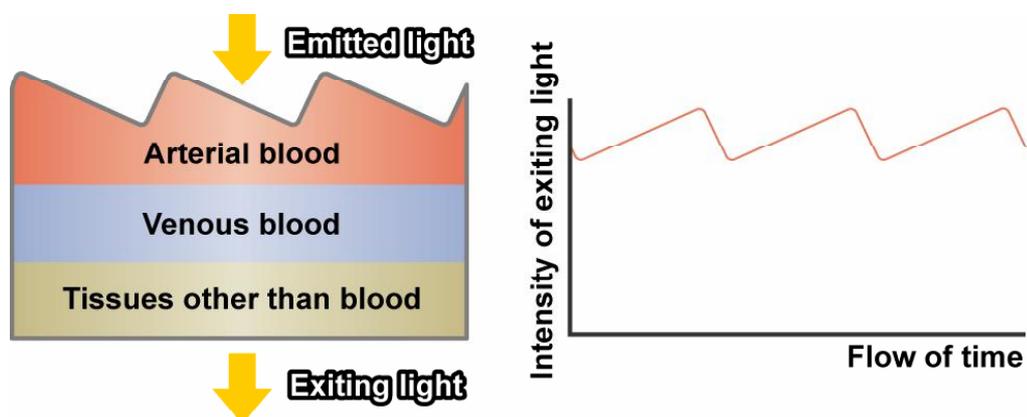
When the amount of HbO<sub>2</sub> is greater, the absorption of red light becomes smaller and the absorption of infrared light becomes larger, resulting in a lower ratio of absorption of the two wavelengths. In contrast, when the amount of deoxygenated hemoglobin is greater, the absorption of red light becomes greater while the absorption of infrared light becomes smaller, resulting in an increased ratio of absorption of the two wavelengths. Thus, the pulse oximeter determines oxygen saturation by measuring the ratio of oxygenated hemoglobin to deoxygenated hemoglobin.

## 10 How can the pulse oximeter measure oxygen saturation, even though the light from the pulse oximeter has to pass through layers of tissue before it reaches the blood?

Arterial blood pumped from the heart moves through vessels in the form of waves called pulse waves resulting in a change in size of the artery.

However, venous blood does not move in pulse waves. The light emitted into the body is absorbed by arterial and venous blood as well as other tissue, and some continues through the body. However, tissues other than arteries experience no change in size over time.

The following figure shows temporal change in pulse wave signals.



Since tissues other than arterial blood experience no change in size over time, the light passing through the body changes in intensity over time depending on the change in the size of arterial blood layers due to pulse waves. The change in intensity results from the change in size of the arterial blood layer, uninfluenced by venous blood and other tissues. Monitoring changes in the components of the exiting light provides data on arterial blood. Measuring the cycle of the changes in light components also reveals the pulse rate. The pulse oximeter can measure oxygen saturation as well as pulse rate based on the pulsing of arterial blood.

11

## What factors cause errors in the pulse oximeter?

Although the pulse oximeter has many advantages, including high precision and ease of use for everyone, there are several factors which may cause errors in measurement. Users should note these factors and take precautionary steps.

### 1. Abnormal hemoglobin

Blood may contain abnormal hemoglobins such as carboxyhemoglobin and methemoglobin which do not contribute to oxygen delivery. The dual-wavelength pulse oximeter may be affected by these abnormal hemoglobins.

### 2. Medical dyes

If dyes such as cardio green, intravascular dyes, and indocyanine green have been injected into the blood, they may influence the level of transmission of the red and infrared light.

### 3. Manicure and pedicure

If users wear nail polish, it may absorb the light emitted from the LED, and change the light transmitted through the body, influencing the values calculated.

### 4. Major body motion

Body motion may cause noise that affects the values calculated. When noise, including that caused by body motion, reduces the reliability of the values calculated, the pulse oximeter will display a warning.

### 5. Blood flow blocked due to pressure on arms or fingers

The pulse oximeter measures oxygen saturation based on changes in the blood flow. Therefore, if the blood flow is blocked, correct measurement becomes impossible. In addition, if the fingers are flexed at a uniform pace (if, for example, grip strength is intensified at a uniform pace on an ergometer), the pulse oximeter may interpret the pressure as changes in pulse rate, causing errors (particularly pulse rate errors).

## 6. Peripheral circulatory failures

The pulse oximeter utilizes blood flow to monitor changes in the amount of light transmitted to calculate values. If the peripheral blood flow is reduced, adequate data may not be obtained, and the result is inaccurate measurement. In this case, it is necessary to promote blood flow by massaging or warming the fingers or measuring other fingers with more regular blood flow.

## 7. Excessive ambient light (panel lamp, fluorescent lamp, infrared heating lamp, direct sunlight, etc.)

The pulse oximeter can usually cancel out the effects of ambient light. However, if the ambient light is too strong, the device will not be able to cancel out the effects, and this may cause errors.

## 8. Ambient electromagnetic waves

If electric appliances such as televisions, mobile telephones, or medical devices which produce high levels of electromagnetic waves are used near the pulse oximeter, the electromagnetic waves from these devices may interfere with accurate measurement.

## 9. Probe attached incorrectly

If the probe is not properly attached, it may detect a variety of noise, resulting in inaccurate measurement.

# 12

## What are permissible levels of SpO<sub>2</sub>?

Usually, levels of SpO<sub>2</sub> range from 96 to 99% in healthy individuals.

However, when patients have pulmonary or cardiovascular chronic diseases at the same time as a common cold or pneumonia, the level of SpO<sub>2</sub> may drop rapidly. SpO<sub>2</sub> lower than 90% is defined as acute respiratory failure. When SpO<sub>2</sub> drops by 3 to 4% from its usual level, even if it is not less than 90%, an acute disease may be suspected.

In some patients, usual levels of SpO<sub>2</sub> may be below 90%. Most other individuals will have fluctuations of 3 to 4%.

Depending on individual pulmonary or cardiovascular conditions, the level of SpO<sub>2</sub> may be relatively higher at rest, even though the level drops considerably during exercise or sleep.

As with "normal" body temperature, the level of SpO<sub>2</sub> varies from person to person. Since pulse oximeters may produce errors, there is no "correct" or "incorrect" result.

Therefore, it is best to record the individual's level of SpO<sub>2</sub> over a long period, and determine their typical range at rest and at various levels of activity so that abnormal decreases can be detected.