OXIMETRY SENSORS:

FACTORS THAT AFFECT ACCURACY

OXIMETRY SENSORS: FACTORS THAT IMPACT ACCURACY

Nellcor Puritan Bennett (NPB) sensors contain small optical components, which are selected to provide reliable, accurate readings. Each sensor contains two light emitting diodes (LEDs) as light sources, and a photodetector which measures the light level. All Nellcor Puritan Bennett (NPB) oximeters and NPB-compatible monitors use specific wavelength-dependent coefficients to accurately calculate oxygen saturation (S_pO_2). NPB sensors are precisely manufactured so that the wavelengths of the LEDs are within a very narrow tolerance of the wavelength expected by the oximeter. A sensor whose LED wavelength is outside of this small wavelength range will cause the oximeter to use inappropriate coefficients in calculating oxygen saturation; as a result inaccurate readings can occur.

Other companies, such as Epic Medical Equipment Services, offer sensors which they claim are compatible with NPB monitors. Though these third party sensors may be *electrically* similar to NPB sensors, testing has shown they use LEDs whose wavelength variation far exceeds NPB's specification. For example, tests have shown that Epic's sensors have wavelengths whose variation is at least *five times greater* than the variation in NPB sensors. Variation like this can result in some sensors being accurate and others being inaccurate. For example, when Epic sensors were tested in our clinical labs, significant inaccuracies were observed (see "Results of EPIC Testing," page 8). The issue for the clinician is that, without specialized equipment, there is almost no way to identify which Epic sensors utilize wavelengths outside the instrument specifications.

Background

The introduction of pulse oximetry into the realm of clinical monitors has provided a safe and simple method of assessing patient oxygenation. With its introduction, clinicians have a way to evaluate oxygenation in a continuous noninvasive and reliable manner.

In order to better understand the importance of precise wavelength tolerances, we need to review the technologies employed in pulse oximetry.

Fundamentals of Oxygen Transport

Arterial blood transports oxygen in two different forms: dissolved in plasma and bound to hemoglobin. The hemoglobin molecule carries 98-99% of all of the oxygen present in the blood. The hemoglobin molecule is a protein contained within the red blood cells. Chemically, it is made up of a "globin" protein and four iron atoms, each enclosed in a "heme" group.

Oxygen has the ability to reversibly bind with the four iron sites on the hemoglobin. The binding of oxygen to the hemoglobin is virtually an "all or none" mechanism. Once one molecule of oxygen is bound, additional O_2 molecules bind rapidly to the three remaining sites. When a hemoglobin molecule has bound four oxygen molecules, it is considered "saturated" and is commonly referred to as oxyhemoglobin (HbO_2). A hemoglobin molecule which is not carrying anything on the four binding sites is referred to as reduced hemoglobin or deoxyhemoglobin (Hb).

The hemoglobin molecule is a very efficient vehicle for transporting oxygen to the tissues. The combination of hemoglobin and oxygen is a loose and reversible one. This allows hemoglobin to pick up and unload oxygen according to the metabolic need and demand.

Technology of Pulse Oximetry

Pulse oximetry provides noninvasive and continuous information about the percent of hemoglobin molecules which are carrying oxygen. "S_pO_2" is commonly used when referring to oxygen saturation readings obtained from a pulse oximeter, to distinguish this measurement from "SaO_2," which is typically measured by a co-oximeter using a blood sample. In combination with the hemoglobin value, the S_pO_2 can provide valuable information about the arterial oxygen content in the blood.

Pulse oximetry combines the principles of optical plethysmography and spectrophotometry to determine arterial hemoglobin oxygen saturation values.

Optical plethysmography uses light to measure time-varying light absorption of tissue in order to observe the time varying blood content of the arterioles. The changes that occur in the absorption of light due to vascular bed changes are reproduced by the pulse oximeter as electronic plethysmographic signals. The oximeter calculates pulse rate by examining these periodic signals.

Spectrophotometry is the measurement of light absorption at different wavelengths. NPB sensors use two light-emitting diodes (LEDs) of different wavelengths: one red and one infrared (IR). The light from the LEDs passes through an arterial vascular bed, which absorbs some of the light. A photodetector, placed on the opposite side of the bed, measures the intensity of transmitted light across the bed. The photodetector transforms the light into an electrical current whose magnitude is proportional to the level of light transmitted. This small current is sent down the shielded sensor cable to the oximeter. By comparing absorption at the two wavelengths, the oximeter can measure the color of the arterial blood, and calculate its oxygen saturation.

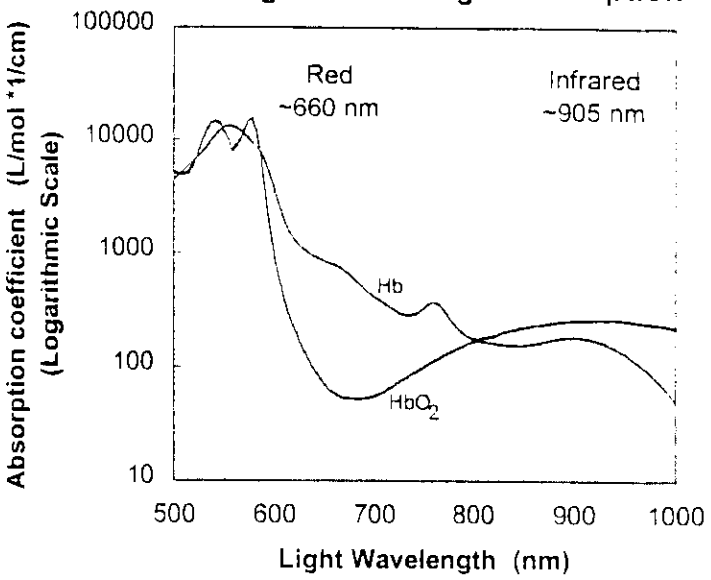
Light Absorption Characteristics of Blood

It is the wavelength-dependent absorption characteristics of blood that make it important for an oximeter to know the precise characteristics of the sensor's optical components. The absorption of light by hemoglobin varies with the wavelength of light used. The absorption of light is also dependent on the amount of hemoglobin which is bound to oxygen. The two curves in Figure 1 show the absorption coefficients of both oxygen-bound (HbO_2) and unbound (Hb) hemoglobin versus light wavelength. The typical red (~660 nm) and infrared (~905 nm) wavelengths used by NPB sensors are also marked. Note that the figure uses a logarithmic scale to accommodate the extremely large range of light absorption.

On a patient, the difference in the intensity of transmitted red and infrared light is caused by the difference in light absorption by oxygenated and deoxygenated hemoglobin in the vascular bed. An oximeter measures the light absorption at both wavelengths, and combines this data with

information on the relative absorption of Hb and HbO_2 at these two wavelengths to compute saturation. When most of the hemoglobin is bound to oxygen, HbO_2 concentration is high and blood absorbs much less red light than infrared light. The corresponding S_pO_2 reading will be ~100%. At low saturation, where most of the hemoglobin is unbound (Hb), the reverse is true.

Figure 1
Hemoglobin and Light Absorption



At shorter wavelengths both HbO_2 and Hb absorb light readily, as shown by the high absorption coefficients in the 500-600 nm range. At wavelengths above approximately 600 nm the absorption coefficients begin to decrease rapidly. The curve for HbO_2 falls fastest, dropping from an absorption peak of ~19,000 at 560 nm to a minimum of ~80 at 660 nm. Above 660 nm the HbO_2 absorption coefficient begins to rise again. The curve for Hb also falls, but not quite as rapidly above 600 nm. Note that both the Hb and HbO_2 absorption coefficients are fairly flat near the IR wavelength (905 nm), but they both change rapidly around 660 nm, which corresponds with the frequency range of red LEDs.

Because the absorption coefficients are so volatile in the red part of the spectrum, small changes in the light wavelength of the red LED cause a large change in the light absorption. In order to assure a correct measurement of S_pO_2, the red LED wavelength must be in a tightly specified range.

Variations in LED Wavelengths

LEDs rarely have exactly the same wavelength. These differences result from the way that LEDs are manufactured. LEDs are solid state devices fabricated on semiconductor wafers in a process similar to that in which integrated circuits or "computer chips" are made. Hundreds of LEDs are created on a single wafer (see Figure 2), which is cut into individual pieces at the end of processing. During fabrication, layers of different material are repeatedly deposited and then partially removed on the wafers to build up the final device. In these processes the wafers are

stacked close together in a cassette and placed in chemical baths, and in deposition chambers or ovens.

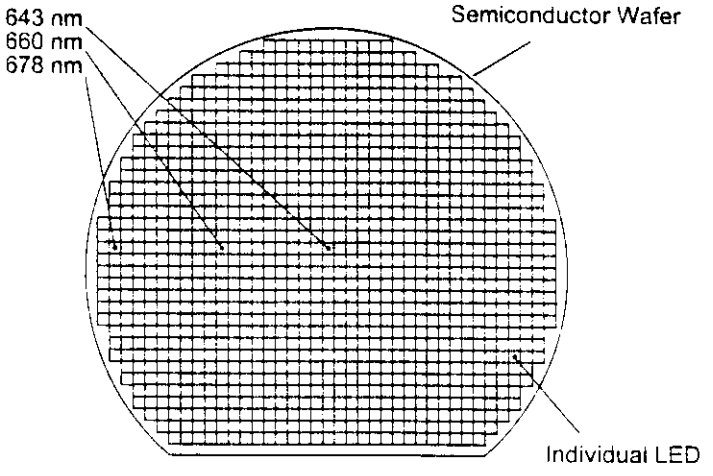


Figure 2.
LED Wavelength varies as a result of slight processing differences

The precise thickness of the different layers that get deposited on a wafer routinely vary across its surface. There are also variations between wafers in the same batch. This is because the location of each wafer in the cassette during processing is slightly different, and because the edges of the wafers are generally more exposed and can react with more fresh reagents. Depending on the manufacturer, the wafer may be 3.5 cm to 6 cm across. The larger the diameter of the wafer, the more challenging it is to achieve a uniform process across its entire surface.

These differences create variations in wavelength between LEDs: even between adjacent LEDs from the same wafer. So though the *average* wavelength for the LEDs on a wafer may be 660 nm, there will always be a range of LED wavelength across a wafer, as shown in Figure 2.

Characterizing Sensors
Before an LED is put into an NPB sensor it is first tested to determine its precise wavelength, and only LEDs which are within a narrow tolerance of the value expected by the oximeter are used in NPB sensors.

The Difference Between Functional Testing and Accuracy Testing
NPB verifies the accuracy of its products with clinical studies under controlled conditions on human subjects. Some sensor manufacturers or their reps use *oximetry functional testers* to "prove" the accuracy of their sensors. In order to understand the difference between these approaches, it is necessary to understand the distinction between functional and accuracy testing.

There are many companies which produce functional testers for pulse oximetry systems. Examples of these are the NONIN® Finger Phantom™, the BIO-TEK® INDEX® tester, and the Clinical Dynamics SmartSat™. It is important for the user to understand what these functional

testers can accomplish with respect to testing the instrument and the sensor. For an instrument, the functional tester can verify that the internal circuitry and software are functioning normally; which implies that the calibration embedded in the instrument has not changed since the unit left the factory. However for a sensor a functional tester can only determine if the sensor is grossly functional and is free of shorts or open circuits. This functional sensor test is similar to checking to see if the second hand on your watch is moving. This determines that the watch mechanism is working, but it does not tell you whether or not the time displayed on your watch is really accurate.

The accuracy of the oxygen saturation reading is dominated by the complex wavelength-dependent optical interaction between the sensor and the patient's tissue. S_pO_2 accuracy can only be evaluated by comparing *in vivo* pulse oximeter readings with measurements made on simultaneously obtained arterial blood samples over the specified range, using an instrument such as a co-oximeter. It is meaningless to compare the calibration accuracy of two brands of oximeter or sensor by comparing the accuracy with which they reproduce "saturation" numbers dialed into a commercially-available electronic tester, because such testers are completely insensitive to light wavelength and there is no relationship between either oximeter's displayed saturation and any physiological phenomenon. The net effect of testing a sensor with any of today's functional testers may be to give the user a false sense of security. These tests results may seem to imply that the sensors will be *accurate* in actual use, but in fact they only imply that the sensor will *give a reading*.

Information from the tester manufacturers confirm this:

> "If you set the INDEX to 75% saturation and the oximeter reads 75%, this does not mean that the oximeter would read correctly on a patient whose SaO2 was 75%. Like the pulse oximeter itself, INDEX is insensitive to subtle sensor changes or manufacturing errors which might cause inaccuracy." - BIO-TEK Instruments, Inc.

> "While the SmartSat Pulse Oximetry Analyzer is a useful tool for quality control testing of pulse oximeter instruments and probes, it is emphasized that since the SmartSat does not expose the pulse oximeter system to arterial blood pluses with a know oxygen saturation, it cannot verify the clinical SpO2 accuracy of a pulse oximeter system. Clinical SpO2 accuracy is defined as the accuracy with which the pulse oximeter system (i.e. instrument and probe together) measures a patient's true oxygen saturation." - Clinical Dynamics Corporation.

NPB Accuracy Testing Protocols

NPB regularly conducts non-invasive studies during which human volunteers have their blood oxygen concentration reduced so that new devices (oximeters or sensors) can be tested across the 70 - 100% saturation range. The purpose of a Non-invasive Controlled Hypoxia study (Accuracy Study) is to validate the saturation accuracy and performance of a test device (pulse oximeter or sensor). In these studies N-200 and/or N-3000 oximeters and sensors that have been previously validated for accuracy against arterial blood samples are used as the control devices. Both of these oximeters have received 510(k) clearance from the FDA.

In the Accuracy Study, human volunteers breathe a reduced concentration of oxygen so that their blood saturation is reduced gradually from its normal level of ~100% to a level of 70% saturation. Values from the reference instruments are compared to simultaneous values from the pulse oximeters and/or sensors under test.

- All subjects are volunteers, and in good health at the time of the study. An anesthesiologist licensed to practice in the state of California is responsible for monitoring the physical state of the volunteer subject. Monitored parameters include: continuous ECG, measurement of inspired oxygen concentration, respiration, CO_2 by capnography, and saturation by pulse oximetry. In addition, the physician is in frequent verbal communication with the subject while the experiment is in progress. The physician measures and records the initial blood pressure to verify normal values before the start of a study. A "crash cart" stocked with appropriate medications and materials is available in the room, in the event of any adverse effects.

- Test and control sensors are attached to the subjects' hands or forehead, nose, ears, or other body surfaces if a sensor is designed for attachment to these sites.

- All sensors are covered with black shields to prevent optical interference between them and other sensors.

- The subject breathes a gas mixture of oxygen and nitrogen through a mask. The gas mixture is varied by slowly lowering the fraction of inspired oxygen (FiO_2), to allow the subject to desaturate. The desaturation to approximately 70% is conducted in a gradual, continuous process, and when data collection is completed, the subject is quickly resaturated to the 100% level. If at any time the subject's oxygen saturation level drops below 70%, the FiO_2 is increased until saturation is greater than 70%.

- Data are collected continuously throughout the desaturation via analog or digital outputs from the control and test instruments. The data are stored in a computer for subsequent analysis.

- Study duration generally does not exceed 30 minutes.

- Saturation values obtained from the control N-200 and/or N-3000 oximeters are plotted and compared to saturation values obtained from the test devices. Data may be analyzed by linear regression ($Y = mX + B$), standard deviation from the line of regression, and standard deviation from the line of identity. Graphs are plotted comparing the control value to the test device value, across the saturation range of interest (70-100%). Figure 4 shows an example from an Accuracy Study.

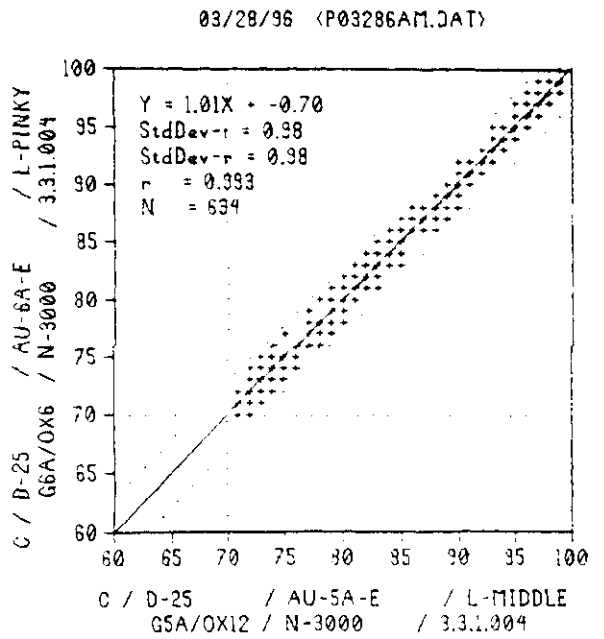


Figure 4
Results of an Accuracy Study

Results of Epic Testing

In accuracy studies on 5 Epic sensors, with two subjects for each sensor, clinical testing showed that the Epic E103 is less accurate than the DS-100A. Nine out of ten tests run with the Epic sensors failed to meet the accuracy specification of the DS-100A (+/- 3 digits for 1 standard deviation). For all the sensors combined the overall accuracy was +/- 4.31 digits. One of the E103 sensors had an accuracy of +/- 6.44 digits (for one standard deviation). Individual differences of up to 14 saturation points were recorded between the control and the Epic sensor.

Summary

NPB's manufacturing process is designed to provide accurate measurement of S_pO_2 when NPB sensors are used with compatible oximeters, since the LEDs will have wavelengths which are within specifications. Because of the nature of the absorption spectra of hemoglobin, if the LED wavelengths are out of specification, inaccurate SpO2 readings can result. A NPB sensor is precisely manufactured so that the wavelength of the LED is within a very narrow tolerance of the wavelength expected by the oximeter. Other manufacturers, such as Epic, use LEDs which are significantly outside of the specification range expected by NPB monitors, and NPB-compatible monitors manufactured by its OEMs and licensees. The result can be inaccurate saturation readings. Nine out of ten tests run with Epic sensors failed to meet the accuracy specification of the DS-100A, and individual differences of up to 14 saturation points were recorded between the control and the Epic sensor.