Conventional and Next Generation Pulse Oximetry
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Conventional and Next Generation Pulse Oximetry

Learning Objectives

- Describe the basic operating principles and four key assumptions of conventional pulse oximetry.
- Define the common failure modes of conventional pulse oximetry.
- Define the signal to noise ratio and indicate an optimum condition.
- List five common sources of noise that can corrupt a pulse oximeter signal.
- List three techniques that conventional pulse oximeter manufacturers have used to make it appear that their pulse oximeters work through motion.
- List two schemes that conventional pulse oximeter manufacturers have used to mask false alarms by reducing the total number of alarms.
Vocabulary

AC - alternating current, it represents the moving or pulsatile component of the pulse oximeter signal.

DC - direct current, it represents the non-moving or non-pulsatile component of the pulse oximeter signal.

Detector - the part of the sensor that receives the signal from the emitter

Dyshemoglobin - hemoglobin in a form that cannot bind with oxygen

Emitter - the part of the sensor that sends out the signal (and produces the visible red light)

False Negative - no alarm when the saturation is abnormal. This can be caused by freezing during a true desaturation

False Positive - a false alarm that indicates the saturation is abnormal when it is not.

Freezing - certain conventional pulse oximeters freeze the display panel when the signal is lost or undetectable. When the signal is found again the system updates, reducing the amount of reaction time during a crisis

Noise - any electronic or mechanical interference that makes it difficult if not impossible to find the signal.

Oximeter - a non-invasive monitor of oxygen saturation that requires a lengthy calibration.

Perfusion Index (PI) - a measurement of perfusion levels using the pulse oximeters infrared signal. PI values range from a low of 0.02% to a high of 20%

Pulse Oximeter - a non-invasive monitor of oxygen saturation that eliminates the need for lengthy calibration but requires a pulse to operate.

Signal Artifact - a corrupted signal that makes it difficult to determine the true signal

Venous Noise - signal artifact caused by venous blood whenever the patient moves.
Understanding the Conventional Pulse Oximeter

A conventional pulse oximeter is comprised of three key components, as seen in figure 2:1 (a sensor, a cable and a monitor). The sensor, (sometimes called the “oximeter probe”) consisting of an emitter and a photo-detector, is directly attached to the measuring site on the patient. The emitter passes red and infrared light through the contact point on the patient to the detector where the light that passes through is measured. The cable, attached to the sensor, then transmits the information from the sensor to the monitor. The monitor filters and analyzes the signals, calculates SpO₂ using a look-up table and displays SpO₂ and pulse rate.

Figure 2:1 Three Key Components of Pulse Oximetry
The Concept

Pulse oximetry uses the principles of spectrophotometry, “if development of color is linked to the concentration of a substance in solution then that concentration can be measured by determining the extent of absorption of light at the appropriate wavelength\(^1\). Figure 2:2 below simplifies these principles.

- Light of a certain intensity \(I_0\) is passed through a substance
- The amount of Light \(I\) that passes through to the other side is then measured
- The difference represents the amount of light absorbed by substance

![Absorption of light by a sample](image)

**Figure 2:2 Absorption of light by a sample**

In spectrophotometry the initial light intensity \(I_0\) is known. The path length, noted in the diagram as “b”, must be kept constant so that the light leaving \(I\) can be measured and the concentration can be calculated.

In 1935, Dr. Karl Matthes was the first to use spectrophotometry to non-invasively measure oxygen saturation, giving birth to the era of non-invasive monitoring. These early oximeters required calibration which took upwards of 30 minutes on a regular basis making them impractical for everyday use.

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The Era of Pulse Oximetry

In 1975 a new era of pulse oximetry began when Takuo Aoyagi, PhD of Nihon Kohden introduced the world’s first commercial oximeter. The new device eliminated the need for laborious calibration. Dr. Aoyagi’s new “pulse” oximeter, as with today’s improved versions, allowed for the comparison of pulsating arterial absorption (AC) and the non-pulsating absorption (DC) components of the blood. By comparing the AC signal to the DC signal, SpO2 readings could be provided in a matter of seconds.

The Four Key Assumptions of Pulse Oximetry

Conventional pulse oximetry sends two wavelengths of light out from the emitter (red and infrared). The photo-detector then attempts to collect as much of the two signals as possible. The diagram below illustrates the pulse oximetry concept. As light moves through the finger, it is absorbed by both non-pulsatile (arterial, venous, bone, tissue or DC, as noted on the diagram 2:3) and pulsatile (arterial, or AC, as noted on the diagram 2:3) blood until it reaches the photo-detector. The relatively slow and constant rate of venous flow allows venous blood to absorb light at a constant rate which is in contrast to the variable absorption rate of arterial blood.

Figure 2:3 Absorption of Light in Pulse Oximetry

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2 Nihon Kohden Available at: http://www.nihonkohden.com/company/techlead.html
The ratio of pulsatile blood (AC) to the sum of all other non-pulsatile components (DC-venous blood, tissue, bone...) is very small - 1:10,000. This means that the pulsating component is extremely small. Although the amount pulsatile blood accounts for very little of the overall signal absorption, it is critical for pulse oximetry.

**The First Key Assumption of Pulse Oximetry:** the only absorbance that fluctuates is arterial blood.

Blood containing high amounts of oxygen is red in color, while oxygen poor blood tends to be bluer in color. The graph below illustrates that HbO₂ (hemoglobin with oxygen or oxyhemoglobin) and Hb (hemoglobin with reduced oxygen levels) absorbs light differently. The red light is absorbed directly in proportion to the amount of color change in the blood, while the infrared signal is used as a reference in the calculation. When using only two wavelengths of light only two parameters can be measured.

**Oxygenated Hb and Reduced Hb Absorb Different Amounts of Red (R) and Infrared (IR) Light**

(Two-wavelength oximeters cannot measure dyshemoglobins)

**Figure 2:4 The absorption of red and infrared light – Hemoglobin and Oxyhemoglobin**

**The Second Key Assumption of Pulse Oximetry:** The only variable light absorbers are oxyhemoglobin and deoxyhemoglobin. In other words, pulse oximetry assumes no dyshemoglobins are present.
The amount of red and infrared signal that is absorbed is then calculated to create a ratio (Figure 2:5). This ratio is directly related to the amount of color change in the blood, which intern is directly related to the amount of oxygen in the blood. The physical size of a patient can affect these ratios, so sensors are designed for a specific patient type (ex. neonates, infants, children, adults, etc…) and specific calculations are formatted accordingly. A study was conducted where healthy volunteers are intentionally desaturated while measuring their red/infrared ratio. Additional blood samples, processed on a CO-oximeter, are also used at specific markers to measure their oxygen saturation. This study allows for the creation of a ‘look up table’ which cross references the noninvasive red/infrared readings to oxygen saturation.

Figure 2:5 Calibration table for SpO₂

Every pulse oximeter is empirically calibrated in this way and has a look-up table like this built into its software.

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3 Masimo FDA submission data
Figure 2:6 Schematic of signal processing of pulse Oximeter

The schematic above (Figure 2:6) illustrates red (R) and infrared (IR) signal processing. The R and IR signals from the sensor are passed through the measuring site and are collected by the detector. The information is then sent to the device processor (blue box) where the signals are filtered to remove as much unwanted internal and external artifact or ‘noise’ as possible. Once the data has been filtered, the red over infrared ratio is measured and a confidence level is assigned by the device. If the data is within an acceptable confidence range, it is sent to the post processor, indicated by the dark blue box, where the look-up table is applied to convert the red/infrared ratio to the corresponding SpO₂ value, which is then displayed on the device. If the filtered data fails to meet the required confidence level, a variety of processes can occur. It is up to the pulse oximeter manufacture to decide how to address questionable data; these methods are discussed in greater detail later in the section.

The Third Key Assumption of Pulse Oximetry: One experimental calibration fits all.

Early in the development of pulse oximeters, low perfusion (PI <0.2%) measurements were not possible. Manufacturers would simply have their pulse oximeters dash out or display zeros when the perfusion reached very low levels. This led clinicians to not rely on pulse oximeters to measure saturation on very sick patients and pulse oximeters became known as a fair-weather friend. When blood samples were drawn and compared only to pulse oximeters reading on patients with good perfusion (PI> 0.2%) the sampled site and the monitored site were usually in equilibrium because of the strong perfusion of the patient. As pulse oximeters improved their low perfusion performance they were able to measure the saturation down to much lower levels (PI 0.02%-0.2%). Since blood samples were not actually taken from the site being monitored during low perfusion, the pulse oximetry values and the blood gas values could be different because of lack of blood flow to the monitored site.

The Fourth Key Assumption of Pulse Oximetry: The measured site and the monitored site are in equilibrium.
Understanding the Four Key Assumptions of Pulse Oximetry

Understanding the four key assumptions of pulse oximetry is critical to troubleshooting common pulse oximetry problems in clinical settings. Let's take a look at the assumptions one at a time.

The only absorbance that fluctuates is arterial blood

Dr. Aoyagi’s discovery, although revolutionary, was fundamentally flawed. His calculations were based on the assumption that venous blood flowed at a constant rate. Today we know that venous blood appears to pulsate during motion. When the finger is placed in motion, and all other variables are held constant, venous blood appears to pulsate (figure 2:7, blue AC). The original calculations, just like the formulas used in all conventional and next generation pulse oximeters of today, do not account for the venous blood pulsation that occurs during movement – calculations are based on the assumption that only arterial blood fluctuates. This occurrence, called venous averaging, happens because Dr. Aoyagi’s calculations included all pulsating components to calculate oxygen saturation. During motion, venous and arterial blood saturation values are averaged together resulting in displayed saturations that are lower than actual saturation.

![Figure 2:7 Components measured during pulse oximetry with motion](image)

Venous averaging is more significant on sick patients

Figure 2:8 illustrates the typical blood flow of a healthy, well perfused patient during motion. When perfusion is good, the amount of oxygen removed from the blood is small; the difference between arterial and venous saturations is also small. Although venous averaging occurs, the oxygen value between venous and arterial saturation is close, and there is not a notable difference between actual saturation and the artifactual number caused by venous averaging. In this scenario, device alarms designed to alert medical personnel of any saturation problems would not sound.
Figure 2:8 Venous Averaging on a Healthy patient with Good Perfusion

Figure 2:9 illustrates this effect of venous averaging on an ill patient with poor perfusion. The reduced speed of the blood flow has caused the body’s blood to deoxygenate more deeply; as a result, venous saturation is now much lower than arterial oxygen saturation.

To the left of the image (Figure 2:9), saturation percents are displayed for both the arterial blood and the venous blood. A conventional pulse oximeter during motion will average the two readings on the left. In this case, the average is a SpO₂ of 74 (to the right of the image), a value considered dangerously low. In a clinical setting, this would trigger pulse oximeter alarms that would alert medical personnel to the problem. Therefore, in many cases movement, especially in very ill or low perfused patients, can cause venous averaging to dramatically overstate desaturation causing pulse oximeter alarms to falsely sound and for medical personnel to take action when none is needed, or to ignore/turn off alarms all together.

Over the years, pulse oximetry has become an industry wide standard in measuring oxygen saturation. During this adoption period, frequent false alarms caused by venous averaging from motion, have caused many medical professionals to turn the pulse oximeters off; not respond; or take action when none is needed. The negative impact of false alarms could not be any more evident than in the neonatal unit where blindness in premature babies has been directly linked to excessive oxygenation due in part to treating infants with increased oxygen due to false desaturation alarms from pulse oximetry devices.
There are only two variable light absorbers, oxyhemoglobin and deoxyhemoglobin.

Dr. Steven Barker from the University of Arizona conducted a study on “The Effect of Carbon Monoxide Inhalation on Pulse Oximetry and Transcutaneous PO₂”. He compared readings from a two wavelength pulse oximeter to results from a laboratory CO-oximeter on a patient with high COHb levels, the results are noted in Figure 2:10. By examining the data, it is easy to see that oxygen saturation from the pulse oximeter was overestimated when compared to the true oxygen saturation as measured by invasive CO-oximetry. Results further revealed that conventional pulse oximeters typically read around 90% SpO2 in the presence of carbon monoxide, even if the patient’s true oxygen saturation is below 50%!

Figure 2:10 The Effect of Carbon Monoxide Inhalation on Pulse Oximetry

Additional studies out of the University of Arizona (Figure 2:11) also revealed that high methemoglobin levels cause conventional two wavelength pulse oximeters to over estimate oxygen saturation as well - this time reading around 85% SpO2 even if the patient’s true oxygen saturation is below 50%! The results of these studies concluded that dyshemoglobins like methemoglobin and carboxyhemoglobin interfere with conventional oximeter saturation values.

Figure 2:11 Effect of Methemoglobin on Pulse Oximetry Measurements
One experimental calibration fits all

Original pulse oximetry data was collected under controlled conditions,

- Patients were healthy with no apparent blood disorder such as anemia
- Digits appeared visibly clean
- Nothing obstructed the emitter signal from passing through to the detector
- Sensors placed and fit properly
- Emitters and detectors were properly aligned.

What if the conditions were not ideal? What would be the result? Imagine the following scenarios

<table>
<thead>
<tr>
<th>Condition</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>The patient had anemia</td>
<td>Saturation would read normal, when in reality overall blood oxygenation would be low</td>
</tr>
<tr>
<td>The finger sensor is placed on a forehead</td>
<td>Emitter and the detector would not line up – although a reading may display, it would not operate within the calibrated parameters</td>
</tr>
<tr>
<td>The sensor is not positioned correctly and light passes around the digit instead of through it</td>
<td>Dubbed the ‘penumbra effect’ – results in erratic and inaccurate readings. See the graphs below (Figures 2:12 &amp; 2:13)</td>
</tr>
<tr>
<td>The patient has long fingernails painted with a dark metallic color</td>
<td>Unfortunately published literature is unclear about the affect that finger nail polish has on pulse oximeter readings, but most articles seem to agree that metallic fingernail polish causes light scattering and can affect its accuracy.</td>
</tr>
</tbody>
</table>
The graph to the left shows plotted data from a properly positioned sensor. Note the close proximity of the data points to the solid line. This tight formation indicates that blood gas values (SaO₂) will be closely approximated by the pulse oximeter values (SpO₂).

Figure 2:12 Calibration table for SpO₂

The graph to the right shows the results of a malpositioned sensor. The red/infrared results do not correlate with the blood gas data and the data points do not line up at all but are scattered randomly. This poor formation indicates that blood gas values (SaO₂) will not be accurately approximated by the pulse oximeter values (SpO₂).

Figure 2:13 Malpositioned N-100 sensor vs. N-200 control, 12 subjects
The measured site and the monitored site are in equilibrium

As the capability of pulse oximetry improved and it became possible to read saturation values to very low levels, a phenomenon called localized hypoxemia has been observed. In this situation, with PI levels below 0.2%, while the blood flow at the measured site (usually at the wrist) is adequate and well oxygenated, the blood flow at the monitored site (usually the finger) is very low (Figure 2:14). The consequence of this low blood flow at the monitored site is that the cells extract a greater amount of oxygen from the slow moving blood than they would if the perfusion was normal. The cells requirement for oxygen does not decrease just because the blood flow is reduced. This then results in a lower saturation value at the monitored site relative to the measured site. So now the pulse oximeter saturation (SpO₂) will be lower than the blood gas value (SaO₂) compared to when the blood flow was normal. While the SpO₂ may not be as close to the blood gas saturation (SaO₂) it can still be of value to monitor the PI and attempt to improve the patient’s peripheral perfusion. As the patient’s peripheral perfusion improves, the PI will increase and the SpO₂ values will again approach the SaO₂ values.

Monitored Site- Pulse Oximetry

Measured Site- ABG CO-oximetry

Figure 2:14 Comparing the measured site and the monitored site
Separating Pulse Oximetry Signals from Noise

In order to accurately measure oxygen saturation, light from the emitter needs to get to the detector with as little noise (non-signal artifact) as possible. Noise is defined as unwanted signal that interferes with the red/infrared signal from the emitter. Common sources of noise that can interfere with the red and infrared signals include:

- other near-by electrical equipment (electrocautery)
- sunlight or any bright lights (light interference)
- sensor movement (decoupling)
- cable movement (triboelectric)
- patient movement (moving venous blood)

![Signal and Noise](image)

**Figure 2:15 Signal and Noise**

Examine the figure 2:15 above. Now imagine placing the signal, represented by the straight line on the left, into the noise, represented by the dark areas on the right. Do you think it would be easy to detect such a signal? Now look at the figure below, can you find the signal?

![Signal and Noise](image)

**Figure 2:16 Signal and Noise**

If you look closely enough, you may be able to see the signal (Figure 2:16). While it is possible to see the signal in this example, it is actually impossible to locate the signal through the venous noise without an advanced signal processing method.
A motionless, healthy subject in an environment with no bright lights and/or other electrical interference, then the signal is optimized and the noise is minimized as shown above (Figure 2:17). In addition, the strength of the signal is directly related to the amount of perfusion, the higher the perfusion the stronger the signal, conversely the lower the perfusion the lower the signal.

The relationship between the signal and noise is called the signal to noise ratio. Pulse oximeter manufacturers have continuously tried to reduce the effects of this ratio by improving the signal and reducing the noise. Figure 2:18 represents three distinct scenarios that affect the signal. Under which condition would you expect to have the most difficulty in finding a signal? Under which condition would it be the easiest to find a signal?

If the signal is high and the noise is low (1) the signal to noise ratio is considered good and the signal would be easy to detect. If the signal is high and the noise is high (2), the signal to noise ratio would be poor and would be difficult to detect. Finally, if the signal is low and the noise is high (3), the signal to noise ratio would be extremely low. In fact, this last scenario describes what happens during motion and low perfusion situations which can result in a situation where it may be impossible to detect the signal.
Conventional and next generation pulse oximeter manufacturers have attempted to optimize the signal to noise ratio by eliminating these sources of noise, with little success. Some pulse oximeter manufacturers have made no attempt and clinicians have learned to adapt. The most difficult noise to eliminate was the noise caused by patient movement or venous noise and so, conventional and next generation manufacturers were never able to find the signal when the patient moved. In early prototypes, the pulse oximeter would display 00 or --- and it was not difficult for clinicians to link movement with inaccurate readings.

**Common Failure Scenarios for Conventional Pulse Oximeters and Techniques Used To Mask These Failures**

Conventional pulse oximeters all suffer from inaccurate readings, or an inability to read, during the following common clinical conditions:

- **Motion**: shivering, restless patient, patient care activities
- **Low perfusion**: hypothermia, shock
- **Excessive ambient light**: phototherapy, bright daylight or florescent lights, OR lights, biliruben lights and infrared warmers in L&D and NICU
- **Electromagnetic interference**: electrocautery in OR

Conventional pulse oximetry vendors applied temporary solutions to address inaccuracies and to reduce the number of alarms during these conditions. Some of these attempts include:

1) **freezing the numbers** (or holding old data for 45 seconds or more) which can lead to falsely high readings (false negatives)
2) **extending the averaging time** (the time over which the information is analyzed)
3) attempting to track the pulse rate with the EKG signal (**Nellcor C-lock**)

These methods do not address the fundamental problem of eliminating the noise, but instead try to read around the noise. As a result, there are a high number of false alarms caused by motion induced venous averaging.

Conventional pulse oximetry technologies also employ alarm management schemes to reduce the number of alarms (not false readings, just reduce the number of alarms). These include:

- Alarm Delay
- SatSeconds (Nellcor)
The problems associated with these approaches include: a reduction in total alarm warnings - both false alarms and true alarms. This can create a more dangerous environment for the patient. Conventional pulse oximeter manufacturers have not been able to solve the problem of reading through motion. In fact, many gave up and deemed the problem unsolvable.

**Probe off detection**

All pulse oximeter manufacturers have had to contend with is the oximeter continuing to display a saturation value even when the probe is not on the patient. Pulse oximeters calculate saturation by measuring the amount of red and infrared light that is absorbed by the detector. The detector gathers data regarding intensity changes in red and infrared light. Changing values that resemble pulsation may cause the oximeter to display an erroneous value. Situations where this can happen include:

- **the operating or emergency room** - In OR and ER situations, it is not uncommon for medical personnel to turn on and attach sensors to the oximeter before attaching it to a patient. The cable typically dangles, exposing the detector to light changes in the room. Aided by circulating air and a slight swinging motion, an artificial saturation may be detected.

- **in the patient’s bed sheets** – the probe comes off the patient and is either on the bed or in the sheets. The sensor light is reflected by the colors in the fabric and can produce a saturation value

- **in a darkened patient room** – the probe comes off in a darkened room and there is no interfering light source to alert probe-off detection. The infrared light bounces off the various surfaces in the room causing the oximeter to display an erroneous saturation value. (note: probe-off detection works best in bright rooms or under bright lights.)