Biomedical Sensor Systems
Laboratory

Laboratory Tutorial: pulse oximetry

Date: May 2019
Place: BMT02002, Stremayrgasse 16, 2. OG
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Short Description:

In this Lab students will perform arterial blood oxygen measurements based on pulse oximetry. The students will apply basic signal processing techniques.

Learning Objectives:

The students are able to ...

- ... name the components of a pulse oximeter and describe their functionality.
- ... understand the principle of (finger tip) pulse oximetry.
- ... determine the pulse rate and oxygen saturation from raw oximeter signals applying signal processing techniques implemented in LabVIEW.
- ... design their own pulse oximeter.

Contents

1 Theory

A (pulse) oximeter is a device intended for the *non-invasive measurement* of arterial blood oxygen saturation and pulse rate. A finger tip pulse oximeter uses the finger tip to acquire the signal.

1.1 Motivation

The instrument transcutaneously estimates oxygen saturation of arterial blood and thus provides vital information about the cardiorespiratory function of the patient. The advantage of this technique is the noninvasiveness and the continuous, immediate availability of the data. It provides real-time oxygen saturation monitoring and can be used in a wide range of medicine, such as anesthesia, emergency medicine, intensive care medicine or even monitoring of patients at home.

1.2 Oxygen transport in blood

The blood is composed of 55 % plasma and 45 % solid components, of which 99.5 % are red blood cells. The haemoglobin in the red blood cells can bind oxygen to ensure oxygen transport. haemoglobin carrying oxygen is called oxygenated haemoglobin (HbO_2) or oxy-haemoglobin, otherwise it is called deoxygenated (formerly, but incorrectly, referred to as reduced) haemoglobin (Hb). The natural frequency of the molecules depends on the oxygen binding enabling optical methods for measuring the oxygen content.

1.3 Oxygen saturation

Generally, the term oxygen saturation defines the percent saturation of oxygen bound to haemoglobin. It is defined as the ratio of HbO_2 to the total concentration of haemoglobin in the blood (HbO_2 + Hb). A haemoglobin molecule can carry a maximum of four oxygen molecules. If 1000 haemoglobin molecules together were carrying 3800 oxygen molecules, then the oxygen saturation level would be $(3800/4000) \cdot 100$ or 95 %.

$$SaO_2 = \frac{[HbO_2]}{[Hb] + [HbO_2]} \cdot 100\,\% \tag{1}$$

There are two abbreviations: oxygen saturation in arterial blood (SaO_2) and oxygen saturation measured by a pulse oximeter (SpO_2). When arterial oxy-haemoglobin saturation is measured by an arterial *blood gas*, it is called SaO_2, the non-invasive measurement of arterial oxy-haemoglobin by a finger pulse oximeter is called SpO_2.

Partial pressure of oxygen dissolved in arterial blood (Sauerstoffpartialdruck) (PaO_2)
PaO_2 is given in mmHg and describes the partial pressure of oxygen dissolved in arterial blood. Figure 1 shows the relation between PaO_2 and SaO_2.

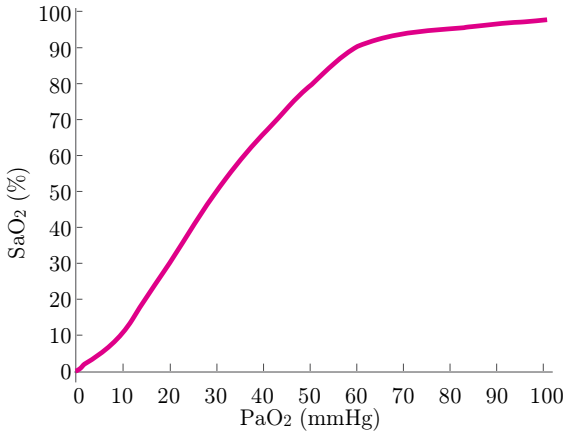

Figure 1: Relation between PaO_2 and SaO_2.

Dyshaemoglobin Dyshaemoglobin are haemoglobin derivatives that are no longer oxygenatable because the binding site for oxygen is blocked at the central iron atom. For example, carboxyhaemoglobin (COHb) is haemoglobin with carbon monoxide at the oxygen binding site. Methaemoglobin (MetHb) is a haemoglobin derivative in which the normally divalent, central iron atom is oxidized to trivalent iron. Trivalent iron is unable to bind oxygen. Thus, methaemoglobin cannot be oxygenated and no oxygen transport is possible.

1.4 Blood oxygen measurement – principles of operation

Oximetry is a term that refers to the optical measurement of oxyhaemoglobin saturation in the blood in general, pulse oximetry describes one special technique, taking advantage of the pulsatile flow of arterial blood. A finger tip pulse oximeter generally contains a dual light source and sends light through translucent parts of the body. Typically, the device uses two LEDs generating red (ca. 650 nm) and infrared lights (ca. 950 nm), and photo detectors (c.f. Figure 2).

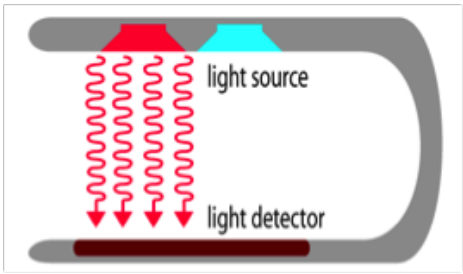

Figure 2: Basic set-up of a finger pulse oximeter

Light absorbance of tissue The Beer-Lambert Law describes the relation of the attenuation of light to the properties of the material through which the light is travelling.

$$I = I_0 \cdot \mathrm{e}^{-\varepsilon(\lambda)[C]d} \,, \tag{2}$$

where I is the intensity of transmitted light, I_0 is the intensity of incident light, $\varepsilon(\lambda)$ is the extinction coefficient of the solute, C the concentration and d is the optical path distance. Beer-Lambert states that the absorbance of light as it passes through a sample is proportional to the thickness of the sample and the concentration of the absorbent. However, Beer's law does not account for the scattering of light.

For the oximetry, one employs the fact that oxyhaemoglobin and its deoxygenated form have significantly different light absorption patterns and thus, the light absorbance of HbO_2 and Hb at the two wavelengths (red/infrared) is different as illustrated in Figure 3. Oxyhaemoglobin absorbs more infrared light than red light, deoxyhaemoglobin more red than infrared light and the difference is quite big at the mentioned wavelengths.

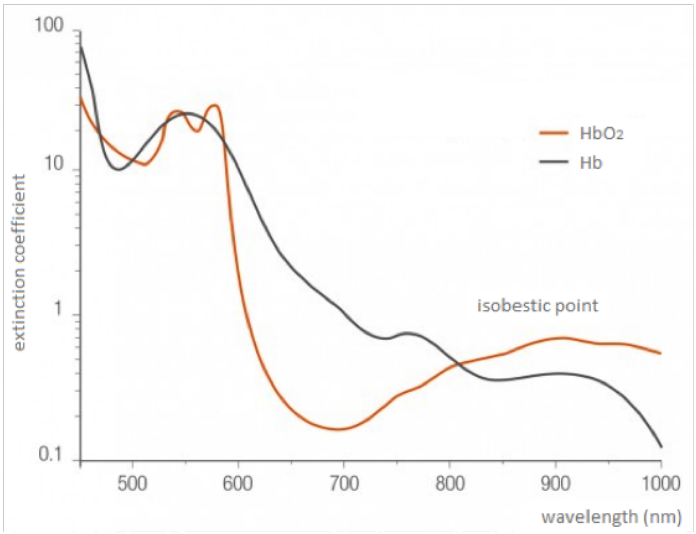

Figure 3: Absorption spectra of Hb and HbO_2. The isobestic point is the wavelength at which the absorption by the two forms of the molecule is the same.

Pulsatile nature of arterial blood Bone, tissue, pigmentation, and venous vessels normally absorb a *constant amount of light over time*. When the heart beats, blood is pushed into the arteries and this pulse propagates throughout the body to the extremities, which can be detected as a momentary increase in the volume of blood in the finger. If a red LED shines through the finger, more light will be absorbed by the blood at the moment the pulse passes through it. Each change in the amount of red light absorbance can be counted as a pulse. The ratio of light absorbed at systole and diastole is translated into an oxygen saturation measurement. The absorption changes can also be used to estimate blood volume of a patient.

Summary "A pulse oximeter shines light of two wavelengths through a tissue bed such as the finger or earlobe and measures the transmitted light signal. The device operates on the following principles:"[1]

- The light absorbance of oxygenated haemoglobin HbO_2 and deoxygenated haemoglobin Hb at the two wavelengths is different.
- The pulsatile nature of arterial blood results in a waveform in the transmitted signal that allows the absorbance effects of arterial blood to be identified from those of nonpulsatile venous blood and other body tissue.
- With adequate light, scattering in blood and tissue will illuminate sufficient arterial blood, allowing reliable detection of the pulsatile signal.

1.5 What do pulse oximeters really measure?

Since Beer's law does not account for the scattering of light, light scattering is still a source of inaccuracy in pulse oximeters. As a result, a direct calculation of SpO_2 is not possible. Instead, pulse oximeters measure a ratio of ratios (ROS) of transmitted red and infrared light intensities. In principle, the ratio of pulsatile and non-pulsatile blood is calculated for the red and infrared LED. These ratios are then related to each other:

$$\mathrm{ROS} = \frac{\frac{\mathrm{ac}_R}{\mathrm{dc}_R}}{\frac{\mathrm{ac}_{IR}}{\mathrm{dc}_{IR}}} \,, \tag{3}$$

with ac = pulsatile arterial blood, dc = tissue, capillary blood, venous blood, non-pulsatile arterial blood, R stands for red light and IR for infrared. This ratio of ratios is then related to a reference table of empirical oxygen saturation values. The values in the reference table depend on the manufacturer's purpose (estimating functional or fractional oxygen saturation) and average dyshaemoglobin and the pH levels of arterial blood obtained from healthy adults breathing hypoxic gas mixtures. As a consequence, in reality, the pulse oximeter measures neither functional nor fractional oxygen saturation unless the dyshaemoglobin and the pH levels of the arterial blood of the subject is by chance exactly the same as the average values of those used in the empirical calibration to create the look-up table.

1.6 Components and architecture of a pulse oximeter

This section gives a brief description of the major parts of a pulse oximeter (c.f. Figure 4). The pulse oximeter tracks the change in light absorbance as the blood pulses. By tracking this peak-to-peak *ac* component, the absorbance due to venous blood or tissue does not have any effect on the measurement.

[1] J. G. Webster, editor. Design of Pulse Oximeters. CRC Press. Taylor & Francis Group, 1997.

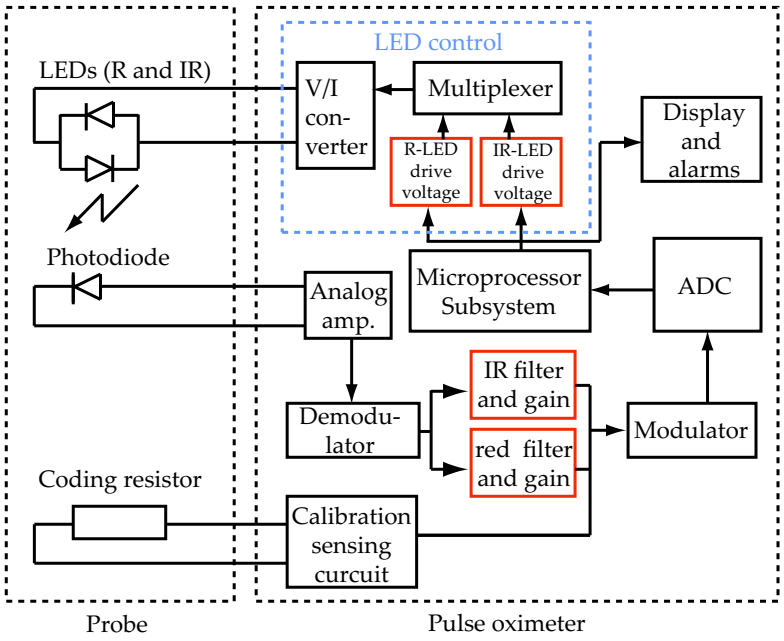

Figure 4: Sample block diagram of a pulse oximeter system. The microprocessor also provides control and timing for the demodulator, modulator and LED control circuits.

LEDs The advantage of LEDs is that they can transmit large intensities of light proportional to the amount of drive current. The two wavelengths chosen for pulse oximetry are typically 650 nm or 660 nm for the red one and 940 nm for the infrared one. Since a photodiode cannot distinguish between red and infrared light, the system alternately turns each LED on and off. The photo diodes (red/infrared) are switched on one at a time, then both off, giving the following sequence at ≈ 500 Hz:

- on/off, off/on, off/off

The timing of the pulsation of the two LEDs is critical, since the photodiode cannot distinguish between different wavelengths. HbO_2 has a higher extinction coefficient than Hb at 940 nm and a lower extinction coefficient than Hb at 660 nm. As a result, as SaO_2 increases (more HbO_2), the absorbance of light increases at 940 nm and decreases at 660 nm. When both diodes are off, ambient light may be detected and compensated for.

The exact wavelength of any single LED can vary by as much as ± 15 nm. For that reason, some manufacturer characterize each LED and code it with a resistor value.

[1] according to J. G. Webster, editor. Design of Pulse Oximeters. CRC Press. Taylor & Francis Group, 1997.

Photodetector The photodetector is the main input device of the pulse oximeter system. The pulse oximeter repeatedly samples the photodiode output while the red LED is on, while the infrared LED is on, and while both are off in order to be able to subtract any ambient light that may be present. The photodetector produces a current which is linearly proportional to the intensity of incident light. This current is then converted to a voltage which is passed on to the pulse oximeter unit for processing. The pulse oximeter measures absorbances at the two wavelengths and uses data from CO-oximeters[2] to empirically look up a value for SpO_2.

Probes There are two main types of probes: transmission probes and reflectance probes. The difference is in the position of the photodetector of the probe, as shown in Figure 5. A reflectance probe has the LEDs and the photodetector on the same side. It must be placed over a point with underlying bone. The standard probe is the finger probe measuring through a finger. It contains a light source (LED) on one side and a light detector on the other side.

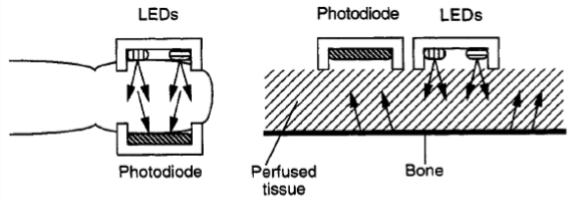

Figure 5: Transmission and reflectance Pulsoximeters.

Analog amplifier and signal processing The output generated by the photodetector is a current that represents the light absorption. This current can be converted to a voltage using an analog amplifier. The change in voltage caused by the pulsation of the arteries is small in comparison to the *dc* portion of the signal. Thus, to enable amplification, the *dc* part of the signal is subtracted from the original signal by the demodulator. The demodulator uses a sample-and-hold circuit to separate samples from the red and infrared LED. The *ac* part of the signals is low-pass filtered in order to remove electromagnetic interference. The signals go through a multiplexer with another sample-and-hold circuit, which modulates the red and infrared signals back into one. The output is digitalized by the ADC. Using the data gathered from the ADC, the microprocessor calculates ROS. Based on this ROS and the value of the coding resistor, the microprocessor uses a look-up table generated by the manufacturer to obtain the final SpO_2 values .

[2]device that measures the oxygen carrying state of hemoglobin in a blood specimen

1.7 Signal porcessing algorithms

Regularly sources of errors dealt with by signal processing algorithms are motion artifacts, reduced saturation levels ($< 80\,\%$) and low perfusion levels. Further significant problems are poor blood circulation and a weak pulse strength, that occurs in cases of insufficient blood pressure or dramatically reduced body temperature. Here it is difficult to separate the true pulsatile component from artifact pulses because of the low signal-to-noise ratio. The amount of light that is transmitted is recorded as an electric signal. The signal is then processed using several signal processing algorithms to estimate the arterial oxygen saturation reliably in the presence of motion and other artifacts. Hence, the algorithms play a major role in transforming the signals collected by the sensors and extracting useful information. To enhance the performance several time- and frequency-domain signal processing algorithms are proposed, e.g., the estimation of oxygen saturation using the Beer-Lambert law.

1.7.1 Estimation of oxygen saturation using the Beer-Lambert law

The volume of blood at the sensor site and the thickness of the finger vary with the arterial pulse. As a consequence, the *path length* d for the light transmitted through the finger changes. Additionally, the precise intensity of the incident light I_0 is not easily determined. Thus, it is desirable to eliminate d and I_0 from the Beer-Lambert law (c. f. Eq.(2)) when estimating the oxygen saturation.

Eliminating the input light intensity as a variable: The intensity of light transmitted through the finger is a function of the absorbance coefficient of both, fixed components (bone, tissue, skin) and variable components, such as the volume of blood and tissue. The unchaning absorptive elements have a thickness d and an absorbance α. The intensity of light modeling the absorption by fixed components (bone, etc...) can be described as

$$I_1 = I_0 \cdot \mathrm{e}^{-\alpha d} \ .$$

Likewise, the intensity of light is weakened by the pulsatile components with varying thickness Δd and relative absorbance α_A

$$I_2 = I_1 \cdot \mathrm{e}^{-\Delta d \alpha_A} \ .$$

Combining both equations leads to

$$I_2 = I_0 \cdot \mathrm{e}^{-[\alpha d + \alpha_A \Delta d]} \ .$$

The effect of light produced by the arterial blood volume is given by the relationship between I_2 and I_1. Defining the change in transmittance produced by the arterial component as $T_{\Delta A}$, we have

$$T_{\Delta A} = \frac{I_2}{I_1} \, .$$

Substituting the expressions for I_1 and I_2 in the above equation yields the following

$$T_{\Delta A} = \frac{I_0 \cdot \mathrm{e}^{-[\alpha d + \alpha_A \Delta d]}}{I_0 \cdot \mathrm{e}^{-\alpha d}} = \mathrm{e}^{-\alpha_A \cdot \Delta d} \tag{4}$$

eliminating the initial intensity I_0.

Eliminating the thickness of the path as a variable To simplify Eq. 4, we apply the ln on both sides and obtain:

$$\ln(T_{\Delta A}) = -\alpha_A \cdot \Delta d \; .$$

Δd can now be eliminated measuring arterial transmittance at two different wavelengths (red and infrared). This results in two equations with two unknowns which are again related to each other

$$\frac{\ln(T_{\Delta A,\mathrm{red}})}{\ln(T_{\Delta A,\mathrm{infrared}})} = \frac{-\alpha_A(\lambda_{\mathrm{red}}) \cdot \Delta d}{-\alpha_A(\lambda_{\mathrm{infrared}}) \cdot \Delta d}$$

If the two sources are positioned at approximately the same location on the finger, the length of the light path through the finger is approximately the same for both LEDs and Δd can be cancelled out:

$$\frac{\ln(T_{\Delta A,\mathrm{red}})}{\ln(T_{\Delta A,\mathrm{infrared}})} = \frac{-\alpha_A(\lambda_{\mathrm{red}})}{-\alpha_A(\lambda_{\mathrm{infrared}})} \tag{5}$$

Equation (5) is now independent of the incident light intensity I_0 and the change in finger thickness as desired. For simplicity, a measured ratio is defined from equation (5) as

$$\mathrm{ROS} = \frac{-\alpha_A(\lambda_{\mathrm{red}})}{-\alpha_A(\lambda_{\mathrm{infrared}})}$$

which corresponds to:

$$\mathrm{ROS} = \frac{\ln\left(\frac{I_{2,\mathrm{red}}}{I_{1,\mathrm{red}}}\right)}{\ln\left(\frac{I_{2,\mathrm{infrared}}}{I_{1,\mathrm{infrared}}}\right)} \; .$$

The oxygen saturation of arterial blood flow can be extracted from independently derived, empirical calibration curves (lookup tables).

1.7.2 Determining the ROS based on intensity measurements in the lab

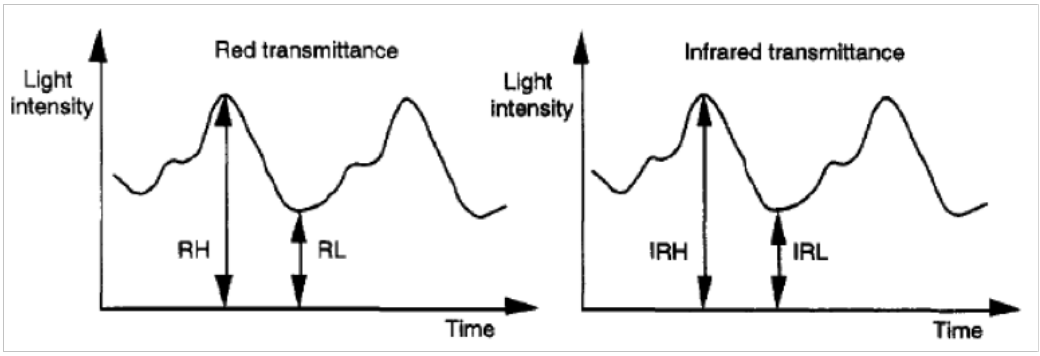

Figure 6: Transmitted light intensity converted into voltage.

Figure 6 shows the light intensity for red and infrared light through the finger. R_L occurs during systole when arterial blood volume is at its greatest, while R_H occurs during diastole when the arterial blood volume is lowest. The ROS can then be computed as:

$$\text{ROS} = \frac{-\alpha_A(\lambda_{\text{red}})}{-\alpha_A(\lambda_{\text{infrared}})} = \frac{\ln\left(\frac{R_L}{R_H}\right)}{\ln\left(\frac{IR_L}{IR_H}\right)}$$

Thus, by measuring the minimum and the maximum emergent light intensities of both the red and infrared wavelengths (R_L, R_H, IR_L, IR_H), a value for the term ROS can be computed. Empirically derived calibration curves are then used to determine the oxygen saturation based on ROS.

1.8 Accuracy and error

1.8.1 Accuracy, Bias, Precision, and Confidence Limit

Accuracy is a measure of systemic error or bias; the greater the error, the less accurate the variable. The accuracy of a measurement is the degree to which it actually reflects what it should represent. Accuracy of pulse oximeter oxygen saturations can usually be tested by comparing with the reference technique – CO-oximeter. Parameters frequently used to represent the degree of accuracy are bias and absolute mean errors.

Bias , in this case, is defined as the mean of the differences between the pulse oximeter readings and the CO- oximeter readings, expressed as

$$\text{bias} = \frac{\sum_{i=1}^{N} x_i}{N} = \bar{x}$$

where x_i is calculated by subtracting the ith CO-oximeter measurement from the corresponding oximeter saturation displayed by a pulse oximeter. N is the total number of measurements. Units are percent saturations.

Precision is a measure of variation of random error, or degree of reproducibility. The dispersion of points around the mean reflects the precision of the measurement. The precision is often described statistically using the standard deviation (SD) of the differences between the pulse oximeter readings and the CO-oximeter readings (x_i) of repeated measurements as in the following equation. Units are percent saturation.

$$\text{precision} = \text{SD} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}} \; .$$

Confidence Limits Most frequently, 95 % confidence limit is used, which is equal to 1.96 times SD for a normal distribution:

$$95\,\%\text{ confidence limit} = 1.96 \times \text{SD} \approx 2 \times \text{SD} \; .$$

The use of bias and precision is helpful in obtaining a clear picture of a pulse oximeter's performance and how this compares to other units or other studies. A unit may be very precise, so that the results are highly reproducible with a low scatter, but have a high bias so that the results are not centered on the true values. In contrast, a unit may have a very low bias, but have poor precision, with values swinging widely from side to side of the true value. In clinical practice a 95 % confidence limit with a precision of at most ±3 % is considered acceptable for most cases.

1.8.2 Sources of errors

Saturation: Accuracy at different levels of oxygen saturation is not the same:

a) Normal saturation (90 % to 97.5 %) Most models of pulse oximeters have a reliable performance in this range, and are well calibrated in this range since it is the most commonly found condition.

b) High saturation (greater than 97.5 %) Pulse oximeter are designed to give a saturation reading of 100 % or less. This limits the potential for positive errors and makes precision calculations difficult to interpret in this high range. Even though precision calculations cannot be determined in a biased way due to the positive errors, the correct oxygen saturation is not critical in this range, because since the oxygen saturation is over 97 %, the patients are in favorable conditions and require no urgent medical attention.

c) Low (hypoxic) saturation (less than 80 %) Pulse oximeters have a high potential for errors at low saturations. They are poorly calibrated for saturations below 80 % and the accuracy and precision are worse. First, ethically manufacturers

cannot stimulate severe hypoxia repeatedly in volunteers for calibration purposes and the error can also be explained by a reduction in the signal-to-noise ratio. As saturation decreases, less red light is able to penetrate through the tissues due to a high absorbance of Hb, thus the AC signal becomes weaker. For compensation, the LED-driving current and the photodiode amplifier gain are increased to maintain the AC signal in a usable range. As the gain increases, incidental electrical and physiological noise also increase, thus resulting in a decline in the pulse oximeter's accuracy.

Perfusion: Pulse oximeters require adequate plethysmographic pulsations to differentiate arterial blood absorbance from the other substances (venous blood, tissue, bone...). Significant decrease in peripheral vascular pulsation, like in severe/ accidental hypothermia, vasoconstriction or hypotension may result in insufficient signals to be processed reliably by the oximeter. Most oximeters have the ability to recognize a weak waveform and alert the user of possible problems.

Motion artifacts: As with most medical devices, motion artifacts contribute a significant error to pulse oximetry. The motion artifact is a major problem that is usually due to the patient's muscle movement proximate to the oximeter probe inducing false pulses that are similar to actual pulses. The false pulses can produce incorrect results. These artifacts can be reduced by digital signal processing and averaging the SpO2 values over several seconds before they are displayed.

Optical interference: Ambient light affects pulse oximeters and leads to weak signals. To obtain accurate measurements, potential sources of optical interference must be controlled. Pulse oximeters are designed to reject ambient light by covering the probe site with some tight materials.

Intravenous dyes: During medical procedures, the use of substances such as dyes may be necessary, which can affect the absorbances of the light.

Dyshaemoglobin: Dyshaemoglobins (COHb, MetHb) are abnormal haemoglobins which cannot transport oxygen. The presence of those haemoglobins can cause inaccuracy in pulseoximetry.

Temperature: Exposing the body to cold temperatures may cause changes in peripheral perfusion which also may cause inaccuracy. The temperature dependence of LEDs in pulse oximeter probes is unlikely to affect the measured values. The effect of shifts in wavelength of the LEDs on pulse oximeter accuracy is negligible as the temperature increases from 0 °C to 50 °C. Inaccuracies in pulse oximeter readings at extreme temperatures are more likely to be caused by reductions in peripheral perfusion, rather than a result of the temperature dependence of the LEDs in the pulse oximeter probe. An uncritical decrease in a patient's body temperature does not result in a significant error increase in pulse oximeter readings.

Probe position: Ear and forehead probes generally have a much faster response to changing SpO_2 than finger probes.

Medical conditions: Fortunately, pulse oximetry works well in the majority of cases. Some frequent encounters where the accuracy of pulse oximetry is often questioned are cardiac arrhythmia and myxoma.

Other effects:

- exercise
- nail polish
- anaemia
- abnormal pulses
- non-pulsatile flow (bypass)
- signal to noise ratio (shocked, hypothermia, vasoconstrictors)
- Radiofrequency interference (MRI)

1.9 Reduction of motion artifacts and noise by ECG synchronization

With ECG synchronization (see fig. 7), the pulse oximeter uses the electrocardiographic QRS complex as a timing indicator that the optical pulse will soon appear at the probe. The R portion of the ECG signal is therefore detected and the time delay determined. This method of signal processing passes those components of the signal that are coupled to the ECG (i.e., the peripheral pulse) and attenuates those components that are random with respect to the ECG, like for example motion artifacts or other noise in the signal.

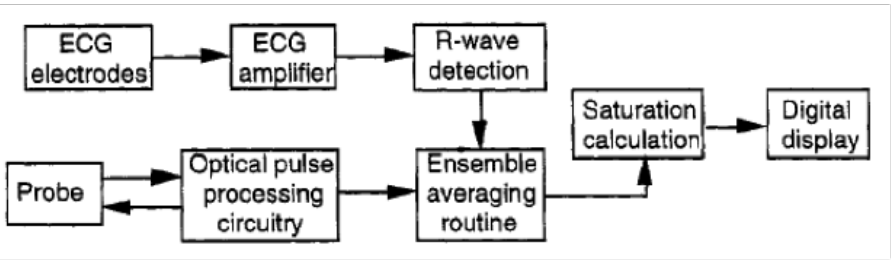

Figure 7: Block diagramm illustrating the ECG processing components

2 Preparatory activities for the lab

A single heart beat has two phases, the systole and the diastole, contributing to the peaks that can be seen on a heart rate monitor. The systole occurs as blood is pushed from the heart through the aorta into the rest of the body, and it is responsible for a larger peak seen on a heart rate monitor. The diastole occurs when blood flows from the body into the right atrium, causing a smaller but distinct peak.

This project measures a person's heart rate by monitoring the amount of blood in the capillaries of the finger. Blood carries oxygen throughout the body using haemoglobin, and the absorption spectrum of oxygenated haemoglobin versus deoxygenated haemoglobin is different. In the red light spectrum (650 nm), the deoxygenated haemoglobin has a higher absorbance than oxygenated haemoglobin. The opposite holds true for the infrared spectrum (950 nm), where oxygenated haemoglobin absorbs more light than deoxygenated haemoglobin.

When your heart beats, blood is pushed into your arteries and this pulse propagates throughout the body to your extremities, which can be detected as a momentary increase in the volume of blood in your finger. If you shine a red LED through your finger, more light will be absorbed by the blood the moment the pulse passes through your finger. Each change in the amount of red light absorbance can be counted as a pulse. This project will focus on building a heart rate monitor based on the principle of the blood volume change during a pulse, however the components and design could be extended to implement a pulse oximeter which distinguishes between oxygenated and deoxygenated blood flow.

2.1 Build Your Own Heart Rate Monitor – Sensor

In this part of the lab you will assemble your own simple heart rate monitor following the instructions of the National Instruments tutorial that you can find here: `http://www.ni.com/tutorial/14246/en/`. Please read the instructions before the laboratory begins.

2.2 Filtering of the signal – preliminary considerations

The raw data acquired from your sensor is disturbed by noise. As a consequence, filtering must be performed in order to achieve a useable signal representing the patient's heart rate. An average person's heart rate lies somewhere between 60 bpm and 100 bpm. It can be assumed that an average adult heart rate increases considerably during exercise with a peak of about 180 bpm. Thus, the frequency of the signal will be about 1 Hz at rest and 3 Hz during exersice.

3 Implementation of the lab

3.1 Build Your Own Heart Rate Monitor

In the first step, you will prepare the sensor for your measurements following the instructions in the lab. The following material will be provided:

- 1 12-inch piece of phone wire 4 wires wide
- 1 Photoresistor with peak sensitivity near 650 nm
- 1 Red LED, with brightness of 10.000 mcd or higher
- 1 Header with at least 4 pins

- Waterproof medical tape, Double-sided tape
- Soldering Iron and Solder (Lötkolben und Lötzinn)
- Heat-shrink (Warmschrumpfschläuche)
- Scissors
- Wire stripper/wire cutter

3.2 Measurements using the Pulse Oximeter

1. For signal acquisition and processing you will use a pre-built board with all necessary circuit components for the detection of the pulse rate.
   - Connect your sensor and make sure it works.
   - Describe the electrical circuit of the pre-built board and explain the function of each circuit component.
   - This should include: amplification, frequency response and cut-off frequency.
2. Registration of pulse rate
   With the subject seated, attach the transducer to the palmar surface of a finger tip. Record the pulse for at least 10 seconds with the subject's arm resting on the lab table. Plot the signal and determine the pulse rate.
3. Interferences
   Examine the following possible factors and describe briefly their effects on your measurements:
   - Motion artefacts
   - light artefacts
   - nail polish