IN-EAR PULSE OXIMETRY IN HIGH ALTITUDE MOUNTAINEERING

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ABSTRACT
According to the world health organization, 40 billion people travel to regions of high altitudes every year. One of the most dangerous diseases according to high altitudes is the acute mountain sickness, caused, inter alia, by reduced partial oxygen pressure. This work reflects the possibilities of a cardio-respiratory acute mountain sickness monitoring with wearable photoplethysmography sensors. Since common photoplethysmographic systems are often applied to peripherals, these systems are affected to hypothermia that may inhibit accurate measurement in critical situations. Therefore, we discuss the usability of the in-ear pulse oximetry for vital monitoring during high altitude activities. For this, we present an in-ear pulse oximeter system for continuous measurement of vital signs. The system is evaluated during a cold-pressure-test to simulate low temperature exposition or to stimulate the endogenous centralization, respectively. Furthermore, high altitude is simulated by reduces partial oxygen pressure in 10 healthy subject (up to 8500m equivalent, ideal conditions). It could be proved, that the sub-dermal perfusion in the inner ear channel is not affected by centralization and thus, enables stable measurement during hypothermia. Blood oxygen saturation (hypoxia) could be measured with high accuracy. Furthermore, the system was tested under a realistic scenario at approximately 3000m in Switzerland with promising results.

KEY WORDS
Wearable sensors, biomedical devices, photoplethysmography, pulse oximetry, high-altitude, mountaineering.

1 Introduction
Health tracking is an everyday commodity for many fitness activities. Besides wearable health trackers that rely on electrocardiography (ECG), first systems based on photoplethysmography (PPG) entered the marked in the recent years. Although they are often used to measure just heart rate, PPG offers many possibilities for vital sign monitoring, like heart rate and its variability, breathing activity, local perfusion, \( S_pO_2 \) and more [1, 2]. Hence, it allows a comprehensive cardio-respiratory monitoring. Therefore, PPG-based wearables seem to be suitable for continuous monitoring of people during activities that may be injurious to health. This can be 1) sport activities at physical performance limit (e.g. marathon running, apnea diving,...) or 2) activities with challenging environmental conditions: very cold or very hot regions (arctic- or desert regions), under water or very high altitude activities.

In the recent decades, mountain related activities like hiking, climbing, mountain biking etc. became more and more popular. Every year, 40 billion people perform activities in high altitudes (HA, 2500m - 5300m) and very high altitudes (VHA, 5300m - 8848m) [3]. Especially VHA bear the risk of low temperatures, dry air, increased ultraviolet light radiation, sudden change in weather or low partial oxygen pressure (\( pO_2 \)).

Related to sea level, \( pO_2 \) is reduced to 50% on 5500m and to 33% on 8500m, approximately the summit of Mount Everest, K2, Kangchenjunga, Lothse and Makalu [3]. According to fig. 1 one can see that the arterial oxygen saturation will be lower than 60% on the summit of Mount Everest. This physiological fact is due to the binding curve of hemoglobin. Low \( pO_2 \) can cause acute mountain sickness (AMS) - the most dangerous implication in VHA mountaineering. Typical symptoms are headache, anorexia, sickness, weakness, sleep disorders, reduced consciousness and death. Due to the increasing high-altitude tourism, monitoring of health constitution becomes an increasingly important aspect for travel agencies, too.

Figure 1. Typical hemoglobin dissociation curve.

In this work, we evaluate the feasibility of a continuous health monitoring at high altitude regarding general...
health constitution and AMS, based on PPG-based monitoring devices. For this, we discuss the differences between peripheral and central PPG measurement regarding VHA specifications. In the following, we present an in-ear multi-wavelength PPG system for robust measurement even during critical situations. The system is evaluated for high altitude measurement from sea level to 8500m regarding $S\text{p}O_2$ measurement and we evaluated the robustness in case of thermal stress.

2 Material and Methods

2.1 Photoplethysmography, Pulse Oximetry and high altitude medicine

PPG, firstly invented by Hertzman on 1938 [4], is a non-invasive, optical method to continuously measure the light absorption in the tissue with a light source and a detector. The light absorption is modulated by the local blood pulsation (perfusion index) and hence, heart rate (and its variability) can be measured. Also breathing activity causes blood pressure changes that can be seen in PPG curves, same with slow rhythm like Trauber-Hering-Mayer waves and thermoregulation processes. By using two or more wavelengths (pulse oximetry), arterial oxygen saturation can be measured by analyzing the color of the blood pulse measured [2]. In conclusion, pulse oximetry deems to be a perfect technique for health monitoring in VHA mountaineering. Table 1 lists the potential of PPG for continuous health monitoring regarding controlled high altitude adaptation (days/weeks) and current health constitution in VHA.

In the past, most systems worked in "transmission mode" (finger, ear lobe, Fig 2), means, the measurement light passes a peripheral body part. This measurement mode is limited to thin body parts that are opaque for the measurement light. As a disadvantage, the periphery is affected by centralization that can be caused by hypothermia, septic shock, high loss of blood and more. Since hypothermia is prevalent during critical situations in VHA, peripheral PPG systems do not provide sufficient measurement robustness.

In contrast, "reflection mode" PPG measures the photons that are reflected from the tissue (Fig. 2). This mode is not limited to few body parts but can be applied on every site that provides sufficient perfusion. Examples for modern reflective PPG systems are Max-fast forehead sensor (Nellcor Inc., USA), Mio Alpha (Medisana AG, Germany) or Cosinuss One (Cosinuss GmbH, Germany).

2.2 in-ear pulse oximetry system

In Fig. 3, the developed MedIT in-ear PPG system can be seen that consists of a reflective PPG sensor chip and a measurement unit. The sensor is applied to the tragus (inner ear channel). Due to the proximity to the brain, a more robust measurement can be assumed during critical situations since the brain is not affected by centralization [5]. The sensor includes two LEDs (red, 760nm, infrared, 905nm) and a pin diode (CiS Erfurt, Germany) that enables pulse oximetry. The wavelengths are chosen due to biological and technical aspects, respectively: 1) The silicon photodiode has the highest sensitivity in the near infrared spectrum and 2) oxygenated and reduced red blood cells show significant contrast for the wavelengths used. At 30 mA Led current, the red light intensity is 2.74mW (4.38dBm) and the infrared intensity is 3.69mW (5.68dBm).

The biocompatible sensor housing is individual customized (personalized) to ensure best wearing comfort and measurement reproducibility. This perfect fitting is an essential requirement for 24/7 monitoring.

The measurement unit serves as an analog/digital interface with MMI and storage option. It was developed
Table 1. PPG-based diagnostics in high-altitude Mountaineering.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High altitude adaption</th>
<th>Health constitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_pO_2$</td>
<td>Changing Binding curve at training</td>
<td>Strong correlation of $pO_2$ (and $S_pO_2$) with AMS</td>
</tr>
<tr>
<td>Heart rate/ variability</td>
<td>Adapted within days to higher level</td>
<td>Sign of life, increased at hypoxia</td>
</tr>
<tr>
<td>Thermal regulation</td>
<td>–</td>
<td>Response to hypothermia</td>
</tr>
<tr>
<td>Breathing activity</td>
<td>Adapted within days to higher level</td>
<td>Sign of life, increased at hypoxia</td>
</tr>
<tr>
<td>Perfusion</td>
<td>Increased erythrocytes density</td>
<td>Sign of life, response at hypoxia</td>
</tr>
</tbody>
</table>

for long-term monitoring and recording and meets the requirements for outdoor activities regarding robustness, battery lifetime (approximately 8h at full 100 SPS sampling speed) and long-term recording of raw data on an internal storage (4GB). The system provides a human interface screen for data visualization. The main processing unit is a 16 bit MSP4301612 mixed signal processor, Texas Instruments Inc., USA.

Further information regarding sensor hardware can be found in [6].

2.3 Studies on thermal stress and high altitude exposition

Studies were performed in order to evaluate the system for high-altitude health monitoring. We investigated the effect of thermal stress and low $S_pO_2$ (high altitude) under controlled conditions during a Cold-Pressure-Test and Hypoxia-Studies.

2.3.1 Thermal stress

Hypothermia can significantly decrease the perfusion in the periphery in order to keep vital organs (core body) on a sufficient temperature. In this case, finger-PPG will no longer provide reliable measurements. However, we expect the inner ear channel to be robust against thermal regulation processes. To evaluate this, we performed human trials with Cold-Pressure-Tests (CPT). During CPT, the participant was 1) in a relaxed situation for baseline measurement (pre-exposition-period), 2) put his hand into ice-cooled water for a defined period of time (two minutes, exposition-period) and 3) removed his hand from the water and stayed in a relaxed position for recovering (post-exposition-period). During this procedure, in-ear measurement was performed, as well as finger-PPG reference (opposite hand), ECG and skin conductance measurement. The study was performed at 14 volunteers.

The perception of the CPT is very individual. Some participants do not feel uncomfortable during the exposition-period. To ensure that participants had an endogenous thermoregulation reaction, only participants were included who showed a clear reaction in skin conductance measurement. The impedance of the skin is the gold standard for objective stress measurement. Overall, 6 subjects were included for further analysis.

2.3.2 High altitude studies

Hypoxia studies have been performed to simulate high altitude exposition. The studies were performed at sea level at the University Hospital of Schleswig Holstein, Luebeck, Germany, in cooperation with Prof. Dr. med. Hartmut Gehring, with positive ethics approval and written informed consent (ethics committee number: 07-023). 10 healthy, young volunteers (3f, 7m, age 22-37, non smoker) were enrolled in the study.

To simulate high altitude, the arterial oxygen pressure was reduced in order to force hypoxia. To reduce arterial oxygen concentration, the mixture of the breathing air of the participant was changed: oxygen was reduced and substituted by nitrogen. Arterial blood oxygen concentration was measured with blood gas analysis and ranged from normal oxygen saturation (99%-100%) to 70% [6]. The alveolar-arterial pressure difference was estimated to be 20 Torr (constant). The oxygen-hemoglobin dissociation curve was approximated with a sigmodial shape according to the Hill equation for cooperative oxygen binding characteristics.

$$Y = \frac{p_0^n}{K + p_0^n},$$

with $Y$=oxygen saturation, $n$=Hill coefficient (2.8) and $K$=dissociation constant (50% at 27Torr). Biological parameters used are in accordance with literature [5]. The approximated curve can be seen in Fig. 4. Physical binding as well as individual differences in oxygen-hemoglobin dissociation were neglected in this work. Hence, this presented results show generalized results under simplified circumstances.

Figure 4. Approximated hemoglobin dissociation curve.
Under ideal conditions, the air pressure can be approximated according to the barometric formula

\[ P(H) \approx p_0 \exp \left( -\frac{H}{H_0} \right), \]  

(2)

with \( p \) = barometric pressure, \( p_0 \) = barometric pressure at sea level and 15 degrees Celsius (101hPa) and \( H_0 = 7990 \)m. Note, that this is just an approximation for the barometric pressure. The formula neglects any weather influences, the gravity acceleration at higher altitudes, inhomogeneous air composition (oxygen percentage is constantly 21%), etc.

Oxygen saturation was measured as follows

\[ R = f(S_pO_2) = \frac{I_{AC, \lambda_1}}{I_{DC, \lambda_1}} \cdot \frac{I_{AC, \lambda_2}}{I_{DC, \lambda_2}}, \]  

(3)

and

\[ S_pO_2 = f(R) = 33R^2 - 152.6R + 176.4 + R_{\text{comp}}, \]  

(4)

with \( AC \) = pulsatile part of the PPG signal and \( DC \) = constant part of the PPG signal [2].

3 Results

3.1 Thermal stress and \( S_pO_2 \)

For analysis of the thermal stress, the surgical stress index (SSI) was used [7]. SSI balances the measured pulse amplitude (PPGA) and the beat-to-beat- intervals \( RR \), coming from the central nervous system. It is defined as

\[ SSI = 100 - (0.7 \times PPGA_{\text{norm}} + 0.3 \times RR_{\text{norm}}). \]  

(5)

PPGA and RR are normalized to 100%. Hence, SSI can be in between 0% and 100%. In different studies, SSI could be proved to be sensitive to stress [8, 9, 7]. Nevertheless, a stress-correlation could only be found for peripheral measurement.

![Box-plot of Cold-Pressure-Test](image)

Figure 5. Box-plot of Cold-Pressure-Test.

Fig. 5 shows the resulting boxplots for pre-exposition, -exposition- and post-exposition-periods for the finger-PPG-system and the in-ear-system. While the finger-PPG-SSI shows a significant reaction during cold-exposition, no reaction can be found for the in-ear system. In detail, the SSI of the finger-system showed a clear reaction for 3 subjects, a weak reaction for 2 subjects and no reaction on one subject. No reaction could be found for the in-ear system.

![Figure 6. Results of the human high altitude study](image)

Figure 6. Results of the human high altitude study. The solid line represents the ideal curve, dots represents \( S_pO_2 \) measurements compared to gold standard (BGA).

In Fig. 6, the measured \( S_pO_2 \) as a function of the estimated altitude can be seen. Every measurement point represents a \( S_pO_2 \) measurement with the in-ear pulse oximeter compared with blood gas analysis. The ideal curve is displayed as solid line. The system shows good measurement performance even at very high altitudes above 8000m. In detail, the measurement error is

- 1.17% for normal oximetry at sea-level,
- 1.14%-1.54% for measurement at HA and
- 2.19% at for measurement at VHA.

3.2 Feasibility study in Wallis, Switzerland

The system was tested under realistic conditions in Wallis, Switzerland during mountaineering at Allalinhorn (4027m). The feasibility study took place in a rope team on glacier, snow and rocks. The ascent to the summit had to be stopped due to a sudden weather change. Anyway, measurements could be performed under difficult cold and wet conditions in between 2900m and 3100m. PPG data in Fig. 7 clearly shows the cardiac activity that can be obtained. However, the measurement was strongly disturbed by motion artifacts. We can summarize, that motion artifacts might be the biggest challenge for in-ear PPG measurement during sport activities. This is due to the fact that the pulsatile \( AC \) component is ten times smaller compared to the \( AC \) part measured in transmissive mode. As a result, the signal-to-noise distance to motion induced disturbances is significantly smaller. Especially rhytmical motion artifacts (like walking) are often in the cardiac frequency band, making it difficult to distinguish between the cardiac signal and the motion noise. Nevertheless, heart rate and \( S_pO_2 \) could be derived from the recorded data.
Figure 7. Feasibility study at Alalinhorn in Switzerland. Cardiac activity and $S_pO_2$ can be obtained from the PPG data.

4 discussion and outlook

In this work, we discussed PPG (and pulse oximetry) in the context of high-altitude mountaineering. The wide diagnostic possibilities, e.g. cardio-respiratory diagnostic, arterial blood oxygen measurement and thermal processes, make PPG ideal for long-term diagnosis in mountaineering. Anyhow, due to the fact that hypothermia makes optical measurements in the periphery inaccurate, conventional finger systems deem to be unsuitable for this purpose. But reflective PPG sensors allow a measurement close to the core body (e.g. close to vital organs). These measurements may not be subjected to endogenous regulation procedures like centralization.

We presented a pulse oximetry system for in-ear measurement. The system includes a customized in-ear sensor and a electronic device for digitalization, human interface and long-term storage. Due to the proximity to the brain, a stable measurement performance can be expected even during hypothermia.

With Cold-Pressure-studies, it could be proved that the in-ear measurement is independent from centralization effects. Hence, accurate performance can be expected even at hypothermia. Furthermore, hypoxia studies were performed to demonstrate the feasibility of $S_pO_2$ measurements even in VHA. The systems showed an overall good performance regarding $S_pO_2$ measurement even at altitudes higher than 8000m.

A feasibility study was performed at Allalinhorn, Wallis, Switzerland. It could be demonstrated that measurements are possible under challenging conditions. Nevertheless, the feasibility study showed that motion artifacts have a big influence on reflective PPG. Although the system showed a good performance under laboratory conditions, further investigations and developments should be done on motion artifact strategies (constant sensor contact pressure, motion detection with accelerometer, etc.).

We conclude that multi-wavelength PPG is the most promising approach for a comprehensive health monitoring during high altitude mountaineering. The measurement should be performed close to the trunk, preferably in the inner ear channel to be independent from centralization and strategies have to be developed to overcome limitations regarding motion artifacts.

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