

The Use of Pulse Oximetry at High Altitude

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Introduction

More than 100 million people visit high mountain regions every year and engage there in sporting activities [1]. Due to the reduced air pressure at altitude, the arterial oxygen saturation (SaO_2) decreases [2,3]. The resulting oxygen deficiency in the tissue is the cause of acute mountain sickness (AMS) in previously healthy individuals [4-6]. It can easily be quantified noninvasively by pulse oximetry [3,7,8]. For this reason, the pulse-oximetric determination of oxygen saturation (SpO_2) during altitude stays is used frequently for the diagnosis of AMS as well as for the assessment of altitude acclimatization status [3,5,7,9-11]. However, pulse oximetry measurements at altitude are much more complex and error-prone than at sea level [8,10,12,13]. Therefore, the use of pulse oximetry at high altitude is viewed critically by experts [8-10,14]. This mini-review describes the special aspects of pulse-oximetric measurements at altitude and gives recommendations on how to perform them.

There is a consensus to use pulse oximetry for monitoring ill persons at altitude [10,14,15]. Concerns exist about possible incorrect measurements due to cold-related deficient blood circulation or movement artifacts [10,16,17]. In our opinion, movement artifacts fundamentally contradict the defined measurement situation of a resting measurement. The test person sits quietly in warm clothing with warm fingers, the sensor is protected from sunlight, while an experienced examiner visually determines the representative mean value of the 2-3-minute measurement interval [5,10,12]. If for whatever reason, the measurement is disturbed due to movement, it is discarded and the measurement is repeated after standardization and optimizing the measurement situation.

During altitude climbing, paO_2 and SaO_2 sometimes drop dramatically. In mountaineers on Mount Everest, values for paO_2 of only 19.1mmHg and SaO_2 of only 34.4% (puncture of the femoral artery) were determined [18]. This is far below the measurement range pulse oximeters are designed for [19]. Therefore, some authors criticize a possible inaccuracy of pulse oximeters in the low saturation range $< 75\%$ [8,10]. Systematic studies, however, showed a deviation of only 1.8% up to a SpO_2 value of 57% [20]. Previous studies have shown a relatively accurate agreement in dogs in the saturation range between 22 - 100%: $R^2 = 0.97$ [21], in children between 35 - 95%: $R^2 = 0.90$ [22] and also in children between 30 - 80%: $R^2 = 0.94$ [23]. Nonin® gives a constant accuracy of ± 2 digits in the saturation range 70 - 100% for the Palm-Sat 2500® [19], which is the device we usually use. Besides, we compared pulse oximetry with the bloody determination of SaO_2 in 14 intensive care patients in the saturation range of 45-98% and could show an excellent correlation of $R^2: 0.99$; $p < 0.001$ [3].

As SpO_2 values have a circadian rhythm, the time point of measurement is essential for the appraisal and comparability of SpO_2 values [24]. Thus, the highest SpO_2 values are found in the morning and they decrease during the course of the day [24,25]. In the course of the night, they rise again, so that values in the first half of the night ($\text{SpO}_{2\text{N1}}$) are normally lower than values in the second half of the night ($\text{SpO}_{2\text{N2}}$) [24]. This circadian rhythm with nightly minima appears to be the normal physiological SpO_2 course, both during the ongoing acclimatization process as well as in long-term adapted highlanders [24,26,27]. Physiologically, this nocturnal drop in SpO_2 is of great importance as a stimulus for EPO secretion and thus for maintaining an elevated hematocrit value - even after acclimatization [25,28,29]. This allows the conclusion that a changed nocturnal SpO_2 course may be an early indicator of a disturbed acclimatization process [24]. In our study, the only mountaineer with an inversed SpO_2 course ($\text{SpO}_{2\text{N1}} > \text{SpO}_{2\text{N2}}$) was also by far the person with the most severe AMS [24].

Because of the periodic breathing typical at altitude, SpO₂ values oscillate considerably making it difficult to determine a representative value [12,30,31]. We were able to demonstrate oscillations in SpO₂ under resting conditions (6,013m) of 17% points (57% -74%) within the 3-minute measurement interval [12]. The decisive factor for the organism at altitude is the mean oxygen saturation [27,30,32]. Therefore, measurements must be carried out over a sufficiently long period to determine a representative mean value [12]. Single point measurements or the use of the highest SpO₂ value of the measurement interval are unsuitable [8,10,33]. A deficient standardization of SpO₂ measurement at altitude and fundamental differences in the study design are most likely the major reasons for the heterogeneous study situation regarding the predictability of AMS by pulse oximetry [7,12,33-37]. With the experience of numerous SpO₂ measurements up to an altitude of 7,100 m [3,12,24,38,39] we regard a strictly standardized, always identical determination of SpO₂ at rest as the mandatory requirement for its use in the context of altitude medicine [12-14]. In addition to the defined time of measurement [24,25] usually in the morning when the patient is fasting, averaging over a longer measurement period (several minutes) is necessary [5,10,12]. We recommend that the measurement interval covers at least 3 cycles of periodic breathing, which corresponds to about 2 - 3 minutes [3,12]. With improved acclimatization, the range of oscillation of the SpO₂ cycles decreases and the determination of the representative SpO₂ value becomes easier, sometimes as simple as at sea level. Then the measuring interval can be reduced [12]. The investigator has to be trained for pulse oximetric measurements at altitude, as he has to determine the representative SpO₂ value visually from the display of the device out of the measurement interval [12]. Nevertheless, even experienced investigators tend to determine the representative SpO₂ value of the measuring interval too high, especially if they measure on their own [12].

If pulse oximetry measurement is performed in the described standardized way and the generally accepted definition of AMS and its latency of 6-36 hours until the outbreak of disease [2,40-42] is addressed in the study design, SpO₂ determination allows the prediction of AMS [3,9,11,36]. Irrespective of this, pulse oximetry measurements at altitude are very susceptible to hyperventilation [15] which often occurs intentionally or unintentionally in the persons being measured [12,38]. This falsifies the SpO₂ measurement considerably. Intensive physical exercise should eliminate this problematic influence of (un-) intentional hyperventilation on the pulse oximetric measurement but could interfere with its accuracy by moving artifacts [16,17]. Therefore, we investigated how heavy physical work with the arms during an ice climb to Les Courtes (3856m) over the Northeast Couloir (800m, 45°-50° steep ice) affects the validity of the pulse oximetric measurement. Even during this extreme activity of ice climbing, enough correct SpO₂ values remain to allow a meaningful assessment of the saturation course [43].

The assessment of an individual's degree of acclimatization to altitude is difficult. We have therefore developed a test procedure

to assess the individual degree of acclimatization [38,39]. The competitive character of the performance test ensured a high degree of motivation for all subjects and this led to a well-standardized test environment. This simple test allows for the determination of an individual's risk for high-altitude illness at higher altitudes. The prediction is based on the lowest SpO₂ found during an uphill run at high altitude (3,371m), combined with the time needed to complete the run. The test results were compared against the severity of high-altitude symptomatology on the summit of Mont Blanc (4,810m). This performance test allows, at a "safe" altitude, the prediction of an individual's risk of developing high altitude illness if they continue to ascend. It allows the determination of the best-acclimatized subjects within a group, for example, before a mission at a greater altitude. In conclusion, the measurement of SpO₂ during physical exercise is more sensitive concerning the individual degree of acclimatization than the measurement at rest [38]. We could also show that the test result improves with increasing acclimatization (faster running time, higher SpO₂) [39].

Conclusion

Pulse oximetry is ubiquitously used during high altitude sojourns. In addition to the possibility of monitoring and therapy supervision of ill and injured patients, it is an important support for the clinical examination of high-altitude climbers on site. However, its application is much more complex at altitude than at sea level and requires an experienced examiner who can include altitude anamnesis, clinical examination and mountaineering aspects in the overall assessment, even during the measurement, but especially when interpreting the saturation values and issuing a resulting recommendation. The measurement during sleep and physical exertion significantly increase its informative value for the early diagnosis of altitude sickness and the assessment of the individual degree of acclimatization. Pulse oximetry is an integral part of the performance test. With this test, it is possible to identify individuals within a group who are very unlikely to get AMS if they continue to climb. This is important in situations where a mission at altitude must be successful.

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