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The correct measurement of oxygen saturation at high altitude

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Abstract

Background Compared to measurements at sea level, measurement of oxygen saturation by pulse oximetry (SpO_2) at altitude differs fundamentally because of the cyclical course of SpO_2, caused by periodic breathing. Therefore, the determination of a representative SpO_2 value is difficult. In the literature, recommendations for a standardized measurement procedure are missing; different studies measure SpO_2 in different ways.

Key question Does the visually determined SpO_2 value correlate with the actual average of the measurement interval?

Methods Four participants of an expedition (6013 m; Pakistan), familiar with pulse oximetry at altitude, wrote down the representative value of the measurement interval of 3 min ($SpO_{2visual}$) according to their individual observation. The used pulse oximeter saved the value for SpO_2 every 4 s. Based on this, the calculated mean ($SpO_{2memory}$) was compared to $SpO_{2visual}$ after finishing the expedition (128 measurements > 2500 m).

Results The spread of the single values within the measurement interval is high (in single cases up to 17%-points) in case of insufficient acclimatization. With increasing acclimatization, the measured values stabilize. $SpO_{2visual}$ differs only marginally (− 0.4%-points; ± 0.8) compared to $SpO_{2memory}$.

Conclusions The correct pulse oximetric determination of SpO_2 at high altitude requires a standardized measurement procedure; the investigator is familiar and trained. Anyway, the measurements have to be done in the continuous mode of the pulse oximeter over a sufficient timeframe (3 SpO_2-fluctuation cycles; 2–3 min). We recommend to record the maximum and the minimum value of the measurement interval and to use a pulse oximeter device with memory function.

Keywords Pulse oximetry · Oxygen saturation · High altitude · Acclimatization · High altitude illness · AMS

Introduction

At high altitude, even lay persons regularly use pulse oximeters to assess individual acclimatization status [1–4]. As the use of pulse oximetry at high altitude is far more complex and prone to errors (cold fingers, movement artifacts, hyperventilation) compared to sea level [1, 5, 6], this is discussed controversially by experts in high altitude medicine [1, 3, 4, 6].

Periodic breathing [7] is the reason for the substantial cyclic oscillation of the oxygen saturation (SpO_2) making it difficult to determine a representative SpO_2 value for the measurement interval. In addition, we could show a circadian rhythm of SpO_2 during studies in the Andes (up to 6354 m) and at Mont Blanc (4810 m). The highest SpO_2 values are found in the morning, and then they decrease over the day followed by a nocturnal increase [8, 9]. Usually values before midnight are lower than those after midnight [9]. Therefore, the time of measurement is essential for the comparability of SpO_2 values [8, 9].

This is probably one of the reasons for the heterogeneous study situation concerning SpO_2 in asymptomatic mountaineers, who later develop high altitude illness [10–16]. However, studies differ concerning SpO_2 determination. O'Conner et al. [10] take the highest SpO_2 value of the 1-min measurement interval for further evaluation whereas Wagner et al. [11] wait until SpO_2 has stabilized over 1 min and take this value. Rarely could we recognize such a stable behavior of SpO_2 after reaching a new altitude we were not

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acclimatized to. Several studies do not mention at all, how they determined SpO_2 values [14, 17, 18]. Because of the typical oscillation of SpO_2 at altitude, single-point measurements are of limited significance [1, 6, 16] for the mean oxygen saturation, which is crucial for the organism [7]. Obviously, the complexity of SpO_2 measurements at altitude is underestimated. However, a standardized measuring procedure is required, especially for scientific evaluations.

For this study, a standardized measuring procedure for the pulse oximetric determination of SpO_2 at high altitudes was used. This procedure is presented and our study evaluates, whether experienced investigators are able to visually determine the representative SpO_2 value of a measurement interval, despite the inconstant display values of the used pulse oximeter device.

Material and methods

Design and background

Due to the cyclical course of the saturation at altitude, one has to measure long enough to receive a representative value. Based on the experience of numerous SpO_2 measurements as high as 7100 m altitude [9, 15, 19, 20], we think averaging over three SpO_2-fluctuation cycles corresponding to a measuring period of 2–3 min is feasible. The determination of the representative SpO_2 value is done by the investigator by intuitively averaging the display values of the pulse oximeter during the measurement interval ($SpO_{2visual}$).

Subjects

Four mountaineers experienced with the use of pulse oximeter at altitude (investigator A and B > 15 years; investigator C > 5 years, investigator D > 2 years) underwent a special training in pulse oximetric measurements of SpO_2 at high altitude prior to this study during a preparation climb in the area of Mont Blanc (Turin hut, 3372 m). During these 4 days of training, each participant determined his own $SpO_{2visual}$ several times in the same way as during the study. Every evening, the corresponding $SpO_{2memory}$ values were calculated and given as feedback. These roughly 30 test measurements per person were found to be very helpful by all investigators to improve their capability of determination of $SpO_{2visual}$.

Measurements

The four investigators performed their own SpO_2 measurements independently with the pulse oximeter PalmSat2500® (Nonin, Plymouth, Minnesota, USA) during an expedition to Yasghil Sar (6013 m; Pakistan) (128 measurements > 2500 m in 16 days). Measurements in the camps were done in the continuous mode of the device after several minutes of rest in a sitting position before breakfast. In addition, measurements during mountain activity were done in the same way after several minutes of rest in a sitting position before food intake. Each investigator focused the display of the device over the whole measurement interval and wrote down the representative $SpO_{2visual}$. The objective for the measurement interval was to cover three SpO_2-fluctuation cycles corresponding to a total measuring time of a maximum of 3 min. The used device PalmSat 2500® stores the value for SpO_2 and heartrate with corresponding time and date every 4 s. The evaluation (mean of the stored values ($SpO_{2memory}$) compared to the corresponding $SpO_{2visual}$ value) was done after finishing the expedition; therefore, no feed-back was given to the investigators during the study. In a diary time/date, name, place, altitude, device number, and barometric pressure were noted for each measurement. This allowed a clear assignment of $SpO_{2memory}$ to the corresponding $SpO_{2visual}$ value of each person at each time point.

In addition to this self-assessment, investigator A performed measurements at the local guides. These measurements were done following the criteria mentioned above with the only difference that the investigator did not determined $SpO_{2visual}$ for himself but for another person (external assessment).

The used pulse oximeter has a company guaranteed accuracy of ± 2%-points of the saturation range between 70 and 100% [21].

Statistical analyses

To compare $SpO_{2memory}$ and $SpO_{2visual}$, we followed the recommendations of Bland and Altman [22].

Data ($SpO_{2memory}$-$SpO_{2visual}$) are presented as mean of the differences (minimal value to maximal value).

As normal distribution was missing (Kolmogorov-Smirnov test), we used Wilcoxon test for paired samples. The level of significance was set at $p < 0.05$. WinSTAT® for Excel was used for statistical analysis.

Results

The most important result of the presented study is the excellent correlation ($R^2 = 0.98$; $p < 0.0001$) of $SpO_{2visual}$ with $SpO_{2memory}$ (Fig. 1), in case the determination of SpO_2 at altitude is done in the way described above. The average measurement interval was 144 ± 48 s; this is enough time to cover 3 to 4 SpO_2-fluctuation cycles and therefore to determine a representative value. There was a tendency that measurements in the camp took longer than during mountain activity.

The mean of the differences ($SpO_{2memory}$-$SpO_{2visual}$) of all self-assessments is − 0.4%-points (− 3.1 to + 1.6%-points).

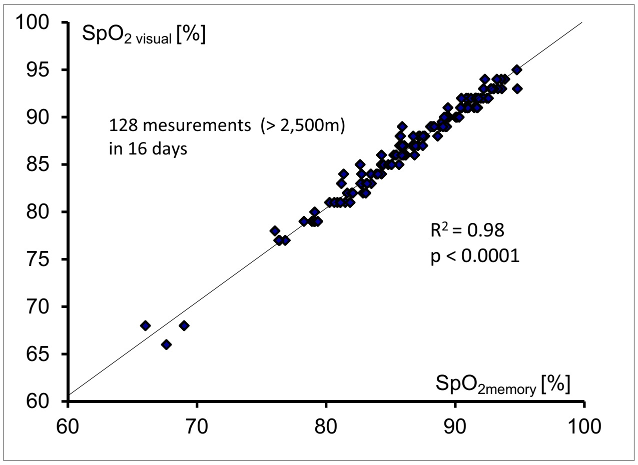

Fig. 1 All visual determined value ($SpO_{2visual}$) compared to the mean of the memorized measurement interval ($SpO_{2memory}$). The excellent correlation is clearly visible

Broken down to each investigator, the mean for investigator A is − 0.1%-points (− 2.0 to + 1.6%-points), for investigator B − 0.1%-points (− 1.2 to + 0.8%-points), for investigator C − 0.9%-points (− 2.7 to + 0.1%-points), and for investigator D − 0.9%-points (− 3.1 to + 0.4%-points). The mean of the measurements of the local guides done by investigator A is 0.0%-points (− 1.3 to + 1.8%-points). For all measurements together (self-assessment and external-assessment), the mean is − 0.3%-points (− 3.1 to + 1.8%-points).

The graphical analysis (Fig. 2) of the differences of $SpO_{2memory}$-$SpO_{2visual}$ in relation to $SpO_{2memory}$ is done following the recommendations of Bland and Altman [22]. This graphic clearly demonstrates the narrow distribution of the single differences around the mean of all differences. The double standard deviation of the differences (± 1.6%-points) is within the accuracy of the method (± 2%-points).

The largest range of single values within one measurement (17%-points: min 57%, max 74%) was found at the summit of Yasghil Sar at 6013 m altitude (Fig. 3a). Despite this, the representative value of the measurement interval was determined relative close ($SpO_{2visual}$ 68%; $SpO_{2memory}$ 66.0%) by investigator A. It is striking, that the SpO_2 increased within the measurement interval, the mean of the 1st half of measuring period (0–90 s) is 62.9%, of the 2nd half (90–180 s) 69.0%. It was the first measurement done after reaching the summit.

After full acclimatization, the SpO_2 fluctuations diminish and constant values can be observed for longer time periods (Abb. 3b). Figure 3 a and b show the SpO_2 course in the same person within only 2 days. However, the measurement in Fig. 3b is done about 3000 m deeper compared to the measurement of Fig. 3a. To this altitude of 3100 m, the mountaineer is fully acclimatized.

The maximum deviation among all measurements amounts to 3.1%-points between $SpO_{2memory}$ (85.9%) and $SpO_{2visual}$ (89%) (Fig. 4). This measurement was done in the morning of day 4 in the base camp at 4500 m altitude. The obvious bisectional SpO_2 course is noticeable, the mean of the 1st half (0–68 s) is 83.5%, and the mean of the 2nd half (72–140 s) is

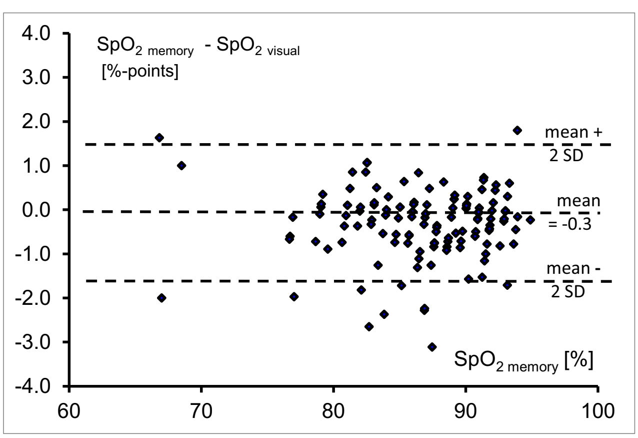

Fig. 2 Bland-Altman plot (23). The differences of each $SpO_{2memory}$-$SpO_{2visual}$ pair are close to the mean difference of all measurements (− 0.3%-points). The doubled standard deviation of the differences (= 1.6%-points) is less than the accuracy of the pulse oximeters (± 2%-points)

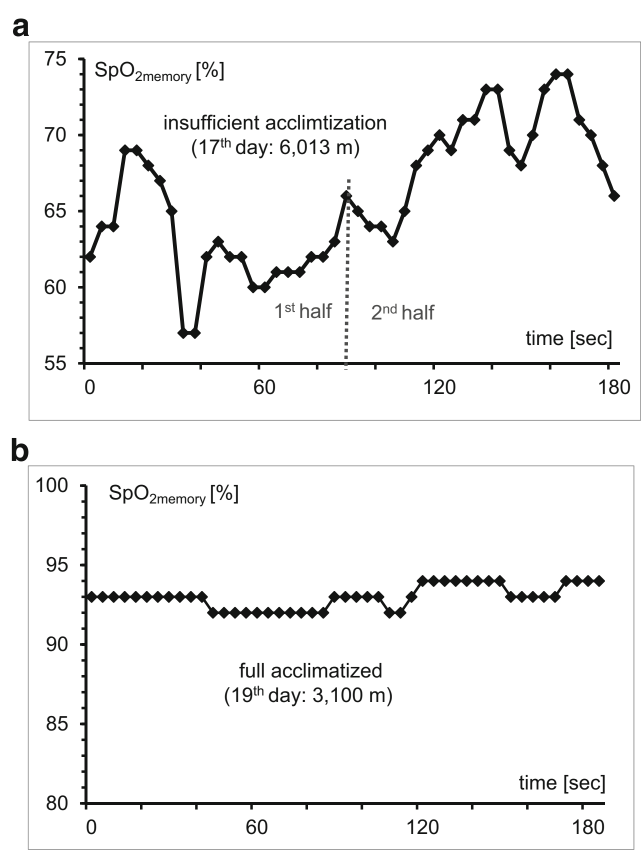

Fig. 3 **a** Insufficient acclimatization with cyclic saturation course (5 fluctuation cycles). The gap between minimum and maximum is 17%-points. $SpO_{2visual}$ is 68%; $SpO_{2memory}$ 66.0%. SpO_2 increases over the measurement interval; mean 1st half: 62.9%, 2nd half 69.0%. Recommend to use a line break **b** Oxygen saturation course in the same person as in Fig. 3a, 2 days later and 3000 m lower and full acclimatized for that altitude. Here, the measurement can be done over a shorter period of time, in the same way as at sea level

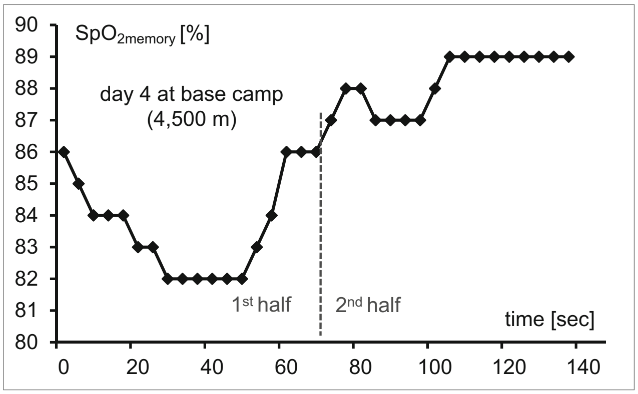

Fig. 4 Measurement with the largest deviation (3.1%-points) between $SpO_{2memory}$ (85.9%) and $SpO_{2visual}$ (89%). The mean of the 1st half is 83.5%, of the 2nd half 88%. The plateau at the end of the measurement interval is obvious; this value was determined as $SpO_{2visual}$ by the investigator

88%. At the beginning of the measurement, SpO_2 decreases with a subsequently continuous increase and formation of a steady plateau at 89% over the last 40 s of the measuring interval. Investigator C noted this plateau as representative $SpO_{2visual}$.

Discussion

This study shows for the first time that experienced investigators are able to visually determine the representative SpO_2 value of a measurement interval correctly at high altitude. In contrast to single-point measurements, the mean SpO_2 value is decisive for the oxygenation status of the organism [7]. Despite substantial fluctuations of SpO_2 within short time periods (see Fig. 3a), the determination of the mean value was with surprisingly high precision. Apart from the great experience of the investigators with pulse oximetry at high altitude, another reason for the high correlation of $SpO_{2visual}$ and $SpO_{2memory}$ is the high motivation of the participants to achieve the best possible match with $SpO_{2memory}$ in this study situation. In general, the differences between $SpO_{2visual}$ and $SpO_{2memory}$ are very small in the whole study.

The before mentioned fluctuations of SpO_2 forbid single-point measurements, a longer observation period is required. Mandolesi et al. [23] calculated SpO_2 as the mean of the saved values of the measurement interval. Based on their empirical experience, they recommend 15 min for the measurement interval, but raise concern that this will be difficult to perform under field conditions. We agree that 15 min and additional time needed for evaluation and calculation of each measurement is not feasible under field conditions. In addition, most expeditions do not have a pulse oximeter with memory function available. Therefore, a practicable solution under field conditions is required. In our opinion, the measurement interval of about 3 min, which we have run, can be implemented in practice.

Particularly noteworthy is that during self-assessment, $SpO_{2visual}$ was determined in average 0.4%-points higher compared to $SpO_{2memory}$. This difference is statistically significant (Wilcoxon test: $p = 0.001$). Even experienced investigators seem to be prone to a small positive bias. In contrast, this deviation towards the "better" value does not occur during the measurements of the local guides. This difference for investigator A (−0.1%-points self-assessment, 0%-points external assessment) is not statistically significant and without clinical relevance.

Besides, one should not overstate these small differences. For the determination of $SpO_{2visual}$, only integers were used, whereas for calculation of the mean values, one decimal point is used. Therefore, the mean difference during self-assessment of −0.4%-points is within the rounding error (and within the accuracy of the method). Nevertheless, even among these experts, there were small, statistically insignificant differences in the quality of assessment. Investigators A and B, who have the longest experience in pulse oximetry at high altitude and regularly perform this in studies, had the lowest deviations (−0.1%-points); in contrast, investigators C and D showed greater deviations (−0.9%-points). In addition, investigators A (−2.0%-points) and B (−1.2%-points) had smaller maximal deviations to the "better" value compared to investigators C (−2.7%-points) and D (−3.7%-points).

Although these differences have no clinical relevance and are less than the accuracy of the measurement method, we conclude that the degree of experience of the investigator correlates with the quality of measured results.

Nine-tenths of our SpO_2 values are > 80%. One can speculate that with more pronounced desaturation, the correct determination of $SpO_{2visual}$ is more difficult and thus its match to $SpO_{2memory}$ worsens. Our results do not confirm this assumption. The measurement on the summit (Fig. 3a) showed the most expressive cyclic saturation course, but the deviation between $SpO_{2visual}/SpO_{2memory}$ was only −2%-points. In the measurement with the largest deviation (−3.1%) (Fig. 4), $SpO_{2memory}$ was 85.9%.

The largest deviations between $SpO_{2visual}$ and $SpO_{2memory}$ occurred when the SpO_2 increased during the measurement interval (Figs. 3a and 4). The reason for this increase is most likely an insufficient resting phase before the measurement was done. The investigators noted the recovery induced higher SpO_2 value as $SpO_{2visual}$. This value probably matches even better with the real resting SpO_2 value, but we cannot prove this. It would have been useful to repeat these measurements after a longer rest period.

Limitations

As no layperson participated a limitation of our study is the lack of a control group—mountaineers not experienced with the use of pulse oximeter at altitude. We can therefore not make any statement about how correctly laypersons measure. Since it is indisputably necessary to determine the SpO_2 over a longer period of time, we first wanted to check whether the visual determination of the mean value of the measuring interval by trained investigators works correctly. For this, we chose the best possible conditions (experienced investigators, study situation with high motivation of the investigators). Since the degree of experience of even our test subjects had an effect on the quality of the results, the need for a comparative study between laymen and professionals can be derived from this with a thorough introduction into the measuring procedure at altitude before measurements are taken. As a practical consequence for not so experienced investigators, the most important thing is to be aware of the problem of periodic breathing at altitude and to perform pulse oximetric measurements in the standardized manner described. With increasing number of measurements, the visual determination of the representative SpO_2 value becomes more and more reliable, especially if a pulse oximeter with memory function is used for self-evaluation.

In addition, the sample of experienced investigators is small. However, a small number of examiners reflect the normal situation during an expedition. Usually, one person carries out all measurements in the entire group. In this respect, we had ideal conditions in our study and therefore no time pressure during the measurements.

Conclusion

The simplicity and high availability of pulse oximeters induce laypersons to measure their own SpO_2 or the saturation of other mountaineers in order to assess the individual acclimatization status [1–4]. However, correct measurements at high altitude, and especially the interpretation of the measured SpO_2 values and their inclusion in a clinical context, requires a physician experienced in high altitude medicine. The massive cyclical fluctuations of SpO_2 within a short time frame, caused by periodic breathing, cause the necessity of averaging SpO_2. If the measurement is carried out in the manner described by an experienced person, the results obtained reflect the oxygenation status of the organism very well.

Another consequence of the presented results is that studies at high altitude using SpO_2 must precisely describe how it was determined. Non-standardized or incorrectly performed pulse oximetry measurements [10] are likely to be a relevant cause of inconsistent study results.

Therefore, we recommend to do pulse oximetry always at the same time of the day, preferably in the morning before breakfast, after a sufficient period of rest and over three SpO_2-fluctuation cycles normally lasting 2–3 min. The average value of this measurement interval must be determined intuitively by the investigator based on the values of the device display. It is helpful to remember the maximum and particularly the minimum value of the measurement interval. Ideally, a pulse oximeter with memory function should be used to check the visually determined values and to train and educate oneself.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the Recommendations of the Commission on Professional Self-Regulation in Science (DFG: Deutsche Forschungsgemeinschaft) [24] and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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