INCREASING RELIABILITY AND INFORMATION CONTENT OF PULSE OXIMETRIC SAHS SCREENING ALGORITHMS

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Abstract: About 3% of people suffer from sleep apnea-hypopnea syndrome SAHS. SAHS is a sleep associated respiratory disorder that negatively affects life quality and life expectancy. It is assumed that more than 80% of SAHS concerned are neither diagnosed nor therapied. Reliable and easy-handling SAHS screening systems are needed. Within this study, the reliability of pulse oximeter as a well-established, non-invasive medical device is examined for SAHS screening. Reliability of existing SAHS screening algorithms will be assessed. Hereby, the focus is on the influence of different desaturation detection strategies and the dependence on thresholds. Critiques on pulse oximetry as SAHS screening device will be responded. In this regard, guideline conform grey area integration in SAHS screening (concerning apnea-hypopnea index AHI between 5 and 15) is recommended. In particular, as by grey area integration an improvement of convenient SAHS screening algorithm reliabilities of about 7.3% in sensitivity and 8.7 % in specificity was achieved even in the most reliable tested algorithm. In a final step, room for improvement of screening results interpretation even without sleep medicine expert skills is indicated. In connection to this, possibilities of short-term frequency analysis of SpO_2 data are demonstrated in its prospects for individualized SAHS screening quality.

1 INTRODUCTION

One of the most common sleep disorders is the sleep apnea-hypopnea syndrome SAHS. SAHS is a sleep associated respiratory disorder, characterized by repetitive breathing cessations. The hourly number of respiratory breath arrests persisting more than 10 seconds (apnea) and reductions of respiratory flow of at least 50% (hypopnea) is called the apnea-hypopnea index AHI. AHI allows a classification of apneic patients (cf. table 1). Threshold for pathological AHI values is between 5/h and 15/h, depending on the coexistence of documented symptoms of excessive daytime sleepiness EDS. (Downey, 2010) (S3-Guideline, Mayer 2009).

SAHS affects about 3% of people in the industrialized countries (Young, 1993) whereat the prevalence increases with male gender and age

Table 1: Guideline for apnea classification (Mayer, 2009).

AHI	SAHS classification
AHI<5/h	SAHS-healthy
5/h ≤AHI≤15/h *without EDS*	SAHS-healthy
5/h ≤AHI≤15/h *with EDS*	SAHS (mild)
15/h < AHI < 30/h	SAHS (moderate)
AHI ≥ 30/h	SAHS (severe)

(WHO World Health Organization). Standard diagnosis for sleep apnea is the polysomnograpy, a multi-sensorial physiological measurement to get a complex sleep profil of the apnea suspect. As the application of polysomnography is labor-intensive and requires high technical expertise (Flemons, 2003), this examination is coupled with an overnight stay in hospital or a aggreditied sleep laboratory. Apart from high costs, required material and upcoming waiting times for an examination, by this

way, patient's inhibitions to undertake such an examination must not be neglected.

Nowadays it is assumes that not even 10-20% of moderate to severe SAHS patients are actually diagnosed (Finkel, 2009), (Kapur, 1999), (Young, 1997), (Esteller, 2008), (Downey, 2010). Thereby an early diagnosis and treatment of SAHS is proved to reduce SAHS associated risk factors such as fragmented structure of sleep, excessive daytime sleepiness, loss of concentration and performance and to augment the risk for cardio-vascular diseases (Wantke, 2008). Untreated SAHS reduces life quality and life expectancy for the patients concerned. The requirement of reliable and easy-to-use SAHS screening systems is obvious and already persecuted on the market. Hence, this makes high demands on the automatic analysis and screening algorithms of pulse oximetric data.

Besides the medical requirements for reliability of the screening results, there are several preconditions that such screening systems should comply for its application. As such, system should be applicable by the patient himself after a short introduction by a general practitioner. An automatic analysis and interpretation of recorded screening data should be possible as sleep medical interpretation skills of recorded data cannot be presupposed (Netzer, 2001). Widely-used and accepted for SAHS screening is the overnight analysis of SaO_2 data by a non-invasive, spectralphotometric pulse oximeter – wearable at the fingertip or earlap. SaO_2 values determined by pulse oximetry are called SpO_2. Pulse oximetry is applied in SAHS for the detection of desaturation in SpO_2 that are caused by apnea and hypopnea events. The number of desaturations per hour is called the desaturation index DI and correlates with AHI. The intensity of respiratory desaturations is depending on the apnea-hypopnea intensity and the inital SpO_2 value before the desaturation event.

Summarizing, pulse oximetry is already an easy-to-use and cost-saving medical analysis device that, based on automatic analysis of data, is sufficient for reliable determination of apnea pretest probabilities. (Wessendorf, 2002)(Mayer, 2009). But final diagnosis, here the experts agree, is not to be adviced by a screening system and should be confirmed in a sleep laboratory.

2 METHODS

Within this study, existing pulse oximetric SAHS screening algorithms based on time domain analysis of $SpO_2[\%]$ data are analyzed. Reviewing existing

algorithms, different strategies for apnea classification are examined in their influence on reliability and comparability of screening results. Hereby, a main focus of attention is given to the dependence on thresholds and time windows under consideration. Actual guidelines consider a grey area $5/h \leq AHI \leq 15$, where an individual diagnosis is indicated. So, we are going to weigh the pros and cons of grey area integration into existing screening algorithms. As future prospect, short-term-frequency analysis of SpO_2 data is presented as a biosignal instrument to sharpen the convenience and quality of patient individual interpretation of SAHS screening results.

2.1 Pulse Oximetric Reference Data

The basis of the following comparisons is the polysomnographic data of the University hospital Puerta del Mar in Cádiz (Spain). It is the data of a standard polysomnogram (Rechtschaffen, 1968) (GES, 2005) including a fingertip pulse oximeter (Erich-Jaeger, model number 70750A19, 2 Bytes sample rate, range 0.0% - 100.0%). The sampling rate of this pulse oximeter is 8 Hz. Desaturations are defined to be at least 4 precentage points decreasing in SpO_2 data without being limited on a certain time interval. The patient collective includes 115 patients of different age, gender and sleep apnea severity code. DI values of patient collective are between 0 and 102; AHI is between 0.01 and 130. Figure 1 shows the correlation amongst the AHI and DI values calculated by the hospital data.
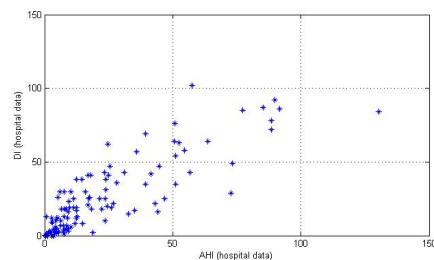

Figure 1: Comparison of DI(hospital) and AHI(hospital).

The total correlation coefficient is 0.8436. In lower AHI values, the correlation increases significantly. In more specific terms, this means that the area of AHI and DI <15 (classifier threshold for apnea healthy and mild apnea patients) are correlated by a coefficient of 0.9293.

For further calculations DI thresholds for apnea classification are equalized to the AHI thresholds of table 1 as there is a direct linear correlation between DI and AHI values within the patient collective. This assumption also coincides to preceding studies

(Torre-Bouscoulet, 2007) (Guideline of SEPAR, 2002). To quantify and assess the reliability of different strategy and threshold compositions in pulse oximetric SAHS screening algorithms, the specificity (SP) and sensitivity (SE) (see equation 1) of the combinations are compared as measurement for the algorithms reliability.

$$SE = \frac{\text{right positive}}{\text{right positive} + \text{false negative}}$$

$$SP = \frac{\text{right negative}}{\text{right negative} + \text{false positive}}$$

Equation 1: Sensitivity (SE) and Specificity (SP).

2.2 Data Preprocessing

Before study analysis, pulse oximetric data undergoes an artifact reduction that excludes unphysiolgical SpO_2 values from data set. Subsequently a moving average filter follows (cf. equation 2). $2m+1$ is the filter width, k is the index of the actual data point and m equals 4 (corresponds to 0.5 seconds of data record). The filter equation is:

$$y_k^* = \frac{1}{2m+1} \sum_{j=-m}^{m} y_{k+j}$$

Equation 2: Moving average filter.

In relation to short-term analysis, SpO_2 data will be downsampled to 1Hz and is filtered by a band pass filter of bandwidth 0.015 Hz - 0.05 Hz. The window length for short-term analysis is 60 seconds with an overlap of 5/6. The estimation of power spectral densities PSD in short-term frequency analysis is made by the Yule-Walker algorithm. Yule-Walker algorithm is an auto-regressive function consisting of the last N measured values $y(t-1)$ to $y(t-N)$ of the signal and a noise component $s(t)$ (cf. equation 3). $s(t)$ is statistically normal distributed. Mean value of noise is 0; standard deviation is σ. The specified order of Yule-Walker algorithm is 30.

$$y(t) = -\sum_{n=1}^{N} a_n y(t-n) + s(t)$$

Equation 3: Estimation of PSD via Yule-Walker algorithm.

3 REALIZATION

By reviewing existing algorithms based on pulse oximetric measurements, different strategies for apnea classification can be identified. Within the following study we will analyse the influence of individual types of algorithms and thresholds on the reliabity and comparability of screening results.

3.1 Reliability of Convenient SAHS Screening Algorithms

Most existing and established algorithms refer to the typical saw tooth desaturation course of SpO_2 data as it results of precursory respiratory events. Figure 2 illustrates such a typical apnea desaturation event including the subsequent resaturation process.

In principle, two accepted approaches in time domain algorithms can be differed:

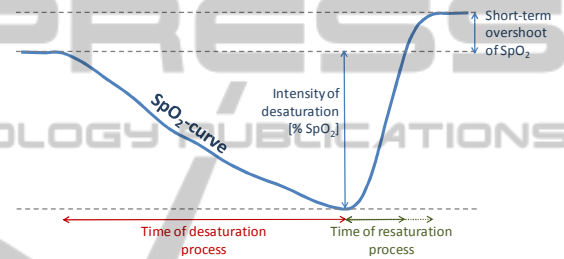1. Desaturation based algorithms
2. Resaturation based algorithms

Figure 2: Typical course of an apnea caused desaturation.

Desaturation bases algorithms consider the slow decrease of SpO_2 values, which occurs shortly after a respiratory event. Frequently used thresholds are 3%, 4% or 5% for desaturation classifiers (Netzer, 2001). Often, there is also a time window indicated to quantify the decreasing rate of SpO_2 data. Thus, e.g. Rauscher (1991) examined a time window of 40 seconds. Resaturation based algorithms focus on the rapid reincrease of SpO_2 values at the end of each respiratory event. To rebalance the oxygen debt, breath frequency at the end of each SAHS events is usually augmented. This results in an accelerated increase of arterial oxygen saturation, possibly with a short-term overshoot of SpO_2 above of initial values (cf. figure 2). Approved thresholds are increases of at least 3% within a time window of 10 seconds (Rauscher, 1991).

The following analysis is motivated by the comparison of the contrast between such diverse desaturation counting strategies. Desaturation (↓) and resaturation (↑) appendages with different percentage thresholds within predefined time periods will be examined in relation to the screening reliability in comparison to the AHI diagnosis. Reliability of desaturation classifiers by at least 3% SpO_2 and 4% SpO_2 decreases (desaturation method) and

accordingly at least 3% SpO_2 and 4% SpO_2 increases (resaturation methods) are analyzed. Predefined time periods are between 10 and 40 seconds generated by corresponding moving time windows over the recorded SpO_2 data. Double count of extended desaturations in neighboring windows is avoided. Precondition of a new event count is a previous significant change of slope. In dependence on the pathological defined AHI between 5 and 15 (cf. table 1), the limit of a pathological amount of desaturations per hour was center-defined by DI≥10 (q.v. GES, 2005) (cf. table 2).

Table 2: DI based SAHS classification.

DI classifier	SAHS classification
DI < 10/h	SAHS-healthy
DI ≥ 10/h	SAHS (mild – severe)

The reliability of the DI classifier were assessed in comparison to the hospital established SAHS-classifier at AHI≥10 (cf. table 3). For this purpose, SE and SP were determined. However, the resulting reliability of all DI based SAHS classifier modifications turned out to be not truly satisfying. Even if SE tends to reliable percentages (maximum: 95.46%, mean: 84.89%), SP remains quite low (maximum: 89.8%, mean: 67.49%) (cf. table 3). The best composed result in respect to reliability was reached by desaturation algorithm with desaturation threshold at 4% in considered time windows of 30 seconds (SE=84.85%; SP=81.6%). According to these analysis outcomes, we agree with the critics complaining about the unsufficient specificity of convenient pulse oximetric algorithms. Nonetheless it may not be forgotten, that separating at DI=10 and AHI=10 is a very hard threshold for SAHS classification. Even actual guidelines (Mayer, 2009) do not draw such a hard classifier line (cf. table 1).
Often, the algorithm results and the AHI diagnosis from the hospital ($AHI_{hospital}$) nearly agree and differ in just a slight amount (total mean deviation of best valued algorithm: -1.681). Nevertheless the final classification sometimes fails because of the results closeness to the classifier threshold.

3.2 Grey Area Integration

According to the German Guideline for apnea classification, subjects with AHI between 5/h and 15/h are considered as a mild apnea patients if there are coexisting EDS. If not, the subject is defined as SAHS-healthy. Identification of EDS is depending on a visit to a doctor and not possible by conventional pulse oximetry screening methods.

Table 3: Reliability of desaturation and resaturation counting thresholds.

SAHS classifier $DI_{algorithm} \geq 10$ vs. $AHI_{hospital} \geq 10$		Mean deviation
Desaturation algorithms		
Algorithm	SP (%)	SE (%)	
3%↓ 10s	77.6	81.82	1.910
3%↓ 20s	59.2	92.42	5.641
3%↓ 30s	57.1	93.94	5.458
3%↓ 40s	53.1	93.94	3.954
Algorithm	SP (%)	SE (%)	
4%↓ 10s	89.8	66.67	-5.264
4%↓ 20s	81.6	78.79	-1.785
4%↓ 30s	**81.6**	**84.85**	**-1.681**
4%↓ 40s	83.7	69.7	-4.133
Resaturation algorithms		
Algorithm	SP (%)	SE (%)	
3%↑ 10s	59.2	89.4	4.476
3%↑ 20s	47.0	95.46	6.893
3%↑ 30s	47.0	95.46	6.015
3%↑ 40s	49.0	95.46	4.232
Algorithm	SP (%)	SE (%)	
4%↑ 10s	81.6	75.76	-2.316
4%↑ 20s	73.5	86.36	0.023
4%↑ 30s	69.4	86.36	-0.603
4%↑ 40s	69.4	87.88	-1.924

Applying this guideline considering the existence of EDS, the previous algorithms will be reviewed. DI values 5/h ≤DI≤15/h are reassigned to a new defined grey area (cf. figure 3). The comparison to hospital values keeps the limit at AHI=10/h.

It is obvious that both, SE and SP increase significantly by grey are integration (cf. table 4). The increase in SE values averages about 7%; and in SP values 2.9%. This becomes apparent in figure 4. Here, the ROC-curves of all tested algorithm constellations are visualized in individual subplots. Within these subplots, a comparison of algorithms with and without grey area integration is provided. The improvement of reliability is evident at prima facie.

Considering the grey area integration, the best reliability is calculated by the 4% decreasing algorithm with a time window of 30 seconds. This is equivalent to the non-grey-area algorithm analysis result, but compared to the same algorithm without the grey area classification group, SP improves by8.7% to SP=90.32% and SE rises by 7.3% to SE=92.16%. Both values, SP and SE above 90% leads to the conclusion that pulse oximetry under the described conditions might be a definitely valuable and reliable device in screening of SAHS suspects.
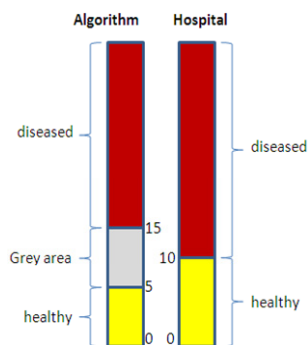
Figure 3: SAHS screening classification algorithm including grey area.
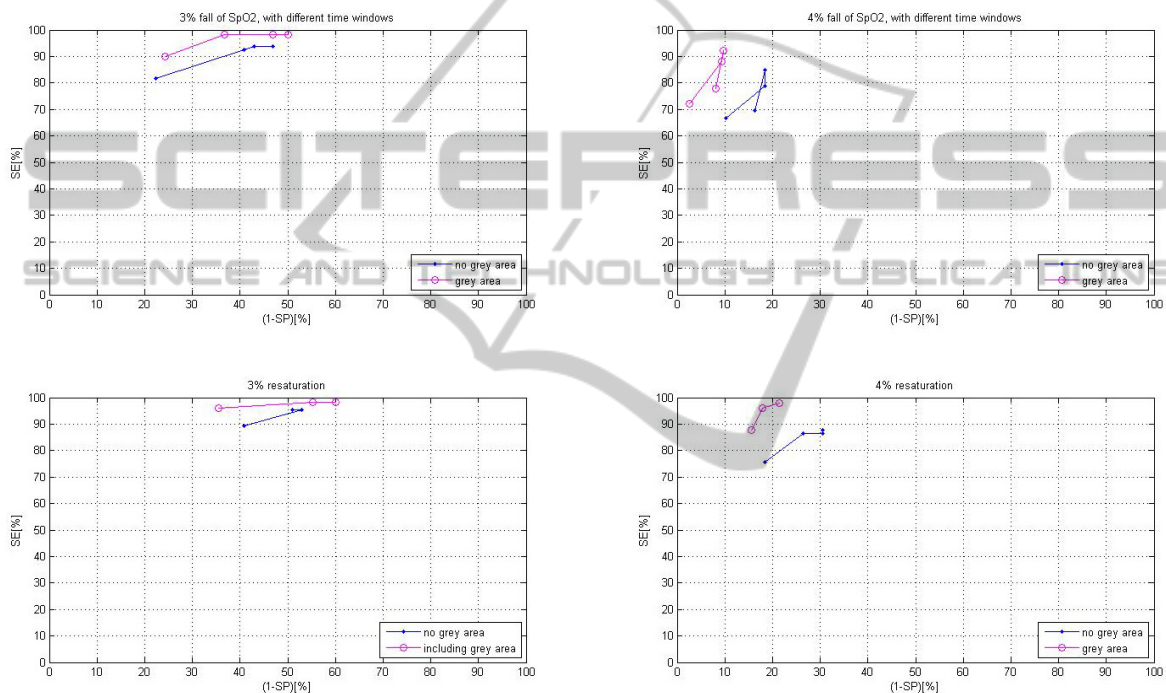

Figure 4: ROC comparing algorithms with and without grey area integration.

Nonetheless, we would emphasize that subject individual conditions are worth to be focused more in screening systems. In this concern, a budding prospect for pulse oximetric SAHS screening will be presented within the following.

3.3 Prospects of Short-term Analysis in SAHS Screening Interpretation

In the past, screening algorithms spent only little attention to the intensity of desaturation events. Thereby, desaturation events may vary between less than 4% and up to 20% or more in SpO_2. For example, on the one hand, some hypopneas even do not induce desaturations corresponding to convenient definitions (e.g. decrease of at least 4%

in SpO_2). On the other hand, and based on lower initial SpO_2 values, the decrease of arterial oxygen saturation proceeds quite fast even within short term respiratory event. Hence, to determine the intensity of SAHS caused desaturations, the duration of desaturation events and the depth of SpO_2 decreases has to be considered as an additional screening result factor. In the fallowing we will derive a method using short-term frequency analysis that permits to depict the intensity of desaturation events in the course of sleep in a quantitative, but easily interpreted graphic image.

Examining the duration of single respiratory caused desaturation events, it becomes apparent that desaturations are predominantly of a duration between 20 and 60 seconds (cf. figure 5).
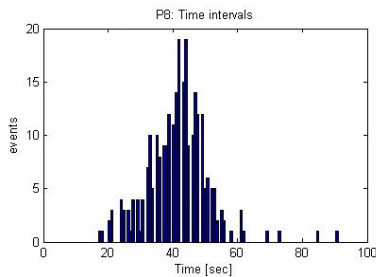
Figure 5: Duration of single desaturation events (e.g. severe apnea patient).

Transfered to frequency domain, this results in a minimum frequency of 0.05 Hz and a maximum frequency of 0.0167 Hz for SAHS typical desaturations (cf. equation 4).

$$f_{desat\_min} = \frac{1}{T_{desat\_min}} = \frac{1}{20\ sec} = 0.05\ Hz$$

$$f_{desat\_max} = \frac{1}{T_{desat\_max}} = \frac{1}{60\ sec} = 0.0167\ Hz$$

Equation 4: Frequency range of typical SAHS caused desaturations.

Because of the saw tooth behaviour and thus sinus likewise course of desaturations in SpO_2, a peak in power spectral density shapes between 0.0167 and 0.05 Hz (cf. (Gross, 2007) (Zamarrón (peak between 0.014 Hz - 0.033 Hz), 1999)). The peak height depends on depth and frequency of the respiratory events within the considered time window.
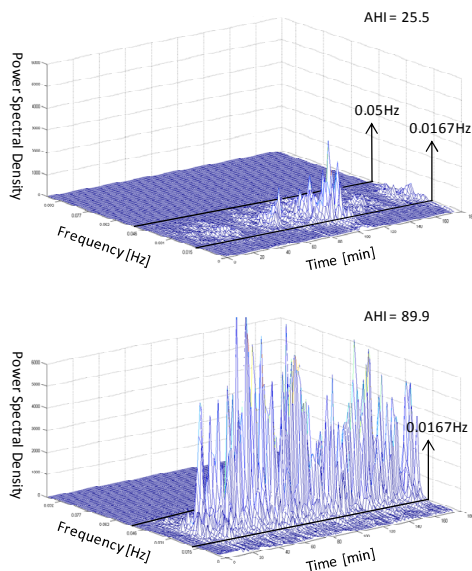

Figure 6: Intensity of desaturation events over sleep time.

The position on the frequency axis gives information about the mean duration of the events within the actual interval. Over the time axis, temporal delimation of events is made possible.

Using short-term frequency analysis on recorded SpO_2 data, the intensity of desaturation events can be visualized in a clear and easy to interpret individual SpO_2 sleep profil (cf. figure 6). Expressed in simplified terms, it can be assumed, that the higher the peaks, the more intensive are the desaturation of the events are. And the more frequent the peaks, the higher the desaturation affected sleep time. As distinguished from time domain presentation of SpO_2 data, non-SAHS characteristic desaturations (e.g. long-term desaturations caused by hypoventilation) are filtered out of the desaturation intensity graphic image.

4 RESULTS

Within this study, we evaluated the reliability of existing SAHS screening algorithms based on overnight pulse oximetric records. We could provide evidence that, in general, resaturation based algorithms are the more specific algorithms and desaturation based algorithms are the more sensitive ones. Nonetheless, and according to actual assessments on pulse oximetry in use for SAHS screening, we have to summarize that the reliability of convenient SAHS screening algorithms is unsatisfactory. Such conclusion was reached turning the attention to the maximum SE and SP results. Thus, all screening algorithms constellations that deliver a sensitivity of at least 85% do not reach a specificity above 75%. None of the tested algorithms stands out by both, a satisfactory high sensitivity and specificity. Such unreliable result corresponds to the comparable findings of many other critics on pulse oximetric screening (Netzer, 2001), (Mayer, 2009) *et alii*.

The mean difference of AHI and DI values was generally quite small, especially in threshold near SAHS patients, we assumed that the lack in reliability must occur mainly because of the hard SAHS classifier threshold. Classifier thresholds are usually set at a fix and defined value like DI = 10. Two patient groups result, those with DI < 10 being the SAHS healthy classified and those with DI ≥ 10 being the SAHS suspects by pulse oximeter screening. The hard threshold and the fact that AHI and DI especially in moderate to severe SAHS patients differ in a certain amount (cf. figure 1) leads to unsatisfying SE and SP results. This assumption

was confirmed by including a grey area characterized by the patient's individual need for diagnosis. The integration of this grey area as an additional classification group for apnea screening could significantly improve the reliablity of SAHS detection. The grey area was implemented in reference to the actual German guideline that also earmarks this area for requiring a patient's individual classification in dependence on coexisting EDS within these thresholds. The best result was obtained by a decreasing type algorithm using a decrease threshold of ≥4% within a moving time window of 30 seconds. The yielded reliability was SE=92.16 and SP=90.32 by a mean deviation of calculated DI vs. real AHI of -1.68/h. In comparison to the same algorithms without grey area consideration, this showed an increase of 7.3% in SE and 8.7% in SP.

In a final manner, we animadvert that generally, information about the intensity of desaturations gets lost within existing SAHS screening algorithms. Extended and deep desaturations (e.g. 40 seconds and 15%) are not differed from shorter and light desaturations (e.g. 20 seconds and 5%). In this regard, we presented the prospects of short-term frequency analysis of SpO_2 data. Thus, individual sleep profiles of overnight desaturation characteristics can be visualized in an easy to interpret three-dimensional graph. This allows drawing conclusions on intensity and repetitivity of desaturation events, even by non sleep medicine specialists.

5 DISCUSSION

According to sleep medicine guidelines, pulse oximetry is a reliable medical device for SAHS pretest probability assessment; keeping in mind that is not able to substitute a sleep medical diagnosis via polysomnography (q.v. Netzer (2001), Wessendorf (2002)). Thus, pulse oximetry is not able to detect e.g. neither AHI nor EDS. Convenient SAHS screening algorithms classify SAHS suspects according to determinable DI values that can differ from patients' AHI. Possible causes of this diversity of DI and AHI are multiple. For example there are:

- Hypopneas, that by definition are decreases in breath flow, but that do not have to be accompanied by pronounced desaturations (Konietzko, 1998).
- Moving artifacts, that may lead to a over-estimation of real DI values (Netzer, 2001).

- Physiological dependences like the initial arterial oxygen saturation or the perfusion at the point of measurement (Oczenski, 2008).
- Dependences on pulse oximeter model (Zafar, 2005).
- Dependences of desaturation classifier definition.

Nonetheless we demonstrated that the reliability of SAHS pretest results yielded to trustworthy SE and SP values ≥ 90% in comparison to AHI diagnosis by polysomnography in sleep laboratory. Against this background and with regard to the high prevalence of SAHS we see a high, but still not exploited potential of pulse oximetry in SAHS screening and pretest application. Furthermore we see the requirement and room for improvement of the analyzability and interpretability of recorded pulse oximetric screening data even by non-sleep medicine experts. In this context, we presented prospects of the short-term analysis of SpO_2 data for improvement of SAHS screening by individual SAHS sleep profiles considering desaturation intensities and its temporal clusters.

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