

JEP^{online}
Journal of Exercise Physiology^{online}

Official Journal of The American
Society of Exercise Physiologists (ASEP)

ISSN 1097-9751

An International Electronic Journal
Volume 5 Number 1 February 2002

Equipment Testing and Validation

COMPARISON OF TWO PULSE OXIMETERS DURING SUB-MAXIMAL EXERCISE IN
HEALTHY VOLUNTEERS: EFFECTS OF MOTION

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ABSTRACT

COMPARISON OF TWO PULSE OXIMETERS DURING SUB-MAXIMAL EXERCISE IN HEALTHY VOLUNTEERS: EFFECTS OF MOTION. **William Kist, Rosemary Hogan, Lorilie Weber-Hardy, Tarilyn Dobey, Kathryn Moss, Mark Wernsman, Marian Minor, Michael Prewitt. JEP^{online}. 2002;5(1):42-48.** Exercise-induced motion artifacts can adversely affect the accuracy of Pulse oximeters (OX) for measurements of arterial oxygen saturation (SaO₂) and pulse rate (PR). The purpose of this study was to compare the SaO₂ and PR measurements at rest and during exercise from two new motion-resistant OX; the Oxi-Reader® and N-395®. Ten apparently healthy subjects volunteered for this study. Subjects were connected simultaneously to both OX and underwent a 16 min sub-maximal exercise treadmill test, including 2 min of standing rest (no motion) at the beginning and conclusion of the test. SaO₂ values less than 92%, or exercise SaO₂ values which decreased 4% from the mean rest SaO₂ value, and PR values 20 b/min less than the preceding min of progressive workload exercise were considered errors. Results revealed statistically significant (p<0.05) correlations between the OX for SaO₂ under both non-motion (r=0.663) and motion (r=0.708) conditions. Likewise, correlations for PR were significant under non-motion (r=0.981) and motion (r=0.485) conditions. However, during exercise, the Oxi-Reader averaged 1.7 PR errors/subject while no PR errors occurred with the N-395. The mean value for the Oxi-Reader PR errors was 63.7±10.8 b/min while the corresponding N-395 PR value was 108.9±15.3 b/min (p<0.001). The Oxi-Reader PR errors during exercise were consistent with resting PR values, not sub-maximal exercise PR values. No SaO₂ readings were in error. The results of this investigation demonstrated that the N-395 performed better than the Oxi-Reader for PR during exercise. However, there was no difference between the OX on resting PR or SaO₂ at rest or during exercise. Thus, during exercise applications, the N-395 can be utilized without electrocardiogram (EKG) monitoring while the Oxi-Reader cannot.

Key Words: Desaturation, Oximetry, Aerobic exercise, Heart rate, Motion-artifacts.

INTRODUCTION

Pulse oximeters (OX) are used to non-invasively monitor arterial oxygen saturation (SaO_2) and pulse rate (PR) during exercise. Being able to conveniently monitor both SaO_2 and PR during exercise has applications such as monitoring chronic obstructive pulmonary disease (COPD) patients during rehabilitation (1). Patients with COPD frequently experience decreased SaO_2 values during exercise and require oxygen administration to maintain SaO_2 values within acceptable ranges. Being able to monitor both SaO_2 and PR with a single instrument is economically advantageous by eliminating the need for an EKG monitor and electrodes.

Unfortunately, motion artifact can adversely affect OX accuracy (2,3). Motion artifacts are caused by changes in arterial perfusion, venous reflux, or pulse waveform changes with altering exercise intensity (1,2,3). Common physiological sources of motion artifact are arm movement, muscle twitch, and excessive grasping of the side-rails of the treadmill. The effect of motion on OX SaO_2 accuracy has been previously studied (4,5), however, little has been reported on the effect of motion on OX-PR accuracy (3,6,7).

Pulse oximeters estimate SaO_2 and calculate PR using a combination of spectrophotometry and pulse-plethysmography (1). Pulse oximeters use two wavelengths of light produced by light-emitting diodes, one in the red and one in the infrared spectrum, and a detector that measures light intensity passing through the fingertip. The OX assumes that pulsation in the light absorbance signal is produced by oscillations in arterial blood volume due to systole and diastole. Differential absorption of light at these two wavelengths and pulsatile changes provides enough information to determine the ratio of oxyhemoglobin to total hemoglobin (SaO_2) and calculate PR.

Two new OX, the Nellcor N-395 (Mallinckrodt Incorporated, St. Louis, MO 63134) and the Oxi-Reader (Allegiance Health Care, McGaw Park, IL 60085; employing Masimo® SET, Signal-Extraction Technology, Masimo Corporation, Irvine, CA 92614), claim to eliminate motion artifacts for both SaO_2 and PR. Oxi-Reader accuracy specifications during motion are $\text{SaO}_2 \pm 3\%$ and $\text{PR} \pm 5$ b/min. N-395 accuracy specifications during motion are $\text{SpO}_2 \pm 3\%$ and $\text{PR} \pm 5$ b/min. The N-395 employs® Oxismart technology. Oxismart technology is a signal processing technique which relies upon three design features: differential amplification of the input signal, application of a series of signal-quality tests, and motion-detection testing of identified pulses (5). The Oxi-Reader employs® Signal Extraction Technology. Signal Extraction Technology utilizes an algorithm which cancels noise signal common to both the red and infrared wavelengths (2). Thus, a tiny arterial pulse can be recognized and purged of even a large motion artifact.

To the best of our knowledge, no published evaluations have compared these two new model OX under motion (or non-motion) conditions. The purpose of this study was to compare the performance of two new motion-resistant OX, the Oxi-Reader and N-395, on SaO_2 and PR during exercise. We hypothesized that motion artifacts could be detected without the use of a criterion reference (arterial SaO_2) by noting non-physiological findings on PR and SaO_2 during the exercise of apparently healthy volunteers.

METHODS

Ten apparently healthy individuals, four females and six males, volunteered for this study (Table 1). Volunteers were screened for participation using questionnaires (cardiopulmonary disease history and physical activity readiness, i.e., PAR-Q), and via spirometric measurement (MultiSPIRO-Sx Platinum, MultiSPIRO Inc., Tempe, AZ) (1,8,9). Spirometry included the forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) measurements. Volunteers also were screened for morbid obesity by measuring height and weight (Continental Scale Works, Chicago, IL) and then calculating body mass index (BMI) (8,9). Subjects with a BMI of less than 35, with no evidence of either obstructive ($\text{FEV}_1/\text{FVC} < 70\%$) or restrictive ($\text{FVC} \% \text{ predicted}$

< 80%) lung disease, cardiac disease, or exercise intolerance were included as subjects in this study (1). Informed consent was obtained. This study was approved by the Institutional Review Board of the University.

Table 1: Subject characteristics.

Age (y)	Height (in)	Weight (lb)	BMI (kg/m ²)	% predicted FVC	FEV ₁ /FVC (%)
42.3±11.22	67.5±3.8	173.7±45	26.6±5.01	103.2±8.52	80.5±6.5

BMI=body mass index; FVC=forced vital capacity; FEV₁= forced expiratory volume in 1 s

To perform this investigation, subjects were connected simultaneously to both OX.. Pulse oximeter sensors (finger probes) were placed on each subject's left hand, one sensor on the index finger and the other sensor on the ring finger. In half of the subjects, a single use Oxi-Reader adhesive sensor (Oxi-Reader Single Patient Use Adult Sensor, P1179) was connected to the ring finger and the Nellcor reusable sensor (Durasensor Oxygen Transducer DS-100A) was connected to the index finger, and vice versa in the other half (3). Thick white adhesive tape was wrapped around the N-395 reusable sensor to eliminate probe movement on the subject's finger and to prohibit light from one OX influencing the other. No subject wore colored nail polish (1). The N-395 response time (averaging time) and sensitivity were set by the manufacturer (automatic and variable) and were not user selectable. The Oxi-Reader response time was set to six seconds (response time appropriate for dynamic exercise) with a normal sensitivity setting (setting for people with apparently healthy cardiovascular status).

Subjects performed a 16 min rest and sub-maximal treadmill test (Naughton). The test protocol included four minutes of non-motion (standing), two minutes occurred at the beginning, and two at the conclusion (recovery period) of the test (8). The remainder of the Naughton exercise test involved 12 minutes of walking. During the first two minutes of exercise, the treadmill speed was set to 1.0 mi/hr and 0% grade. For minutes three and four, the speed was increased to 2.0 mi/hr while the grade remained at 0%. During minutes 5-12, the speed was maintained at 2.0 mi/hr, and the grade was increased 3.5% every two min. Volunteers were encouraged to freely swing their left arm (finger probes on left hand) during the treadmill test while their right hand was placed on the treadmill railing for balance. The Naughton protocol was terminated at 12 min (six METS). Oxygen saturation and PR data for both OX were manually recorded each minute during the test.

Suspicious (in error) PR readings during exercise were determined by noting a decreased PR (≥ 20 b/min) relative to the immediate previous minute. For example, if the grade for minutes 6, 7, and 8 were 3.5, 7.0, and 7.0%, and the corresponding PR were 110, 65, and 130 b/min, then the 65 b/min PR was considered suspicious because it was at least 20 b/min lower than its previous minute PR value. The expected physiological PR response to this type of progressive workload protocol would be for PR to increase or remain at approximately the same level throughout the protocol (1,8,9). During sub-maximal exercise testing, most individuals reach a steady-state heart rate (± 5 -10 b/min) by the by the third minute of a given workload (9). However, the Naughton protocol evolved to become a low-level intensity exercise protocol useful for testing cardiac-diseased subjects, with many subjects reaching a steady-state heart rate within two min at a given stage (10). The Naughton protocol increases workload one MET per stage (two min) (8). It is our experience with the form (8) of the Naughton protocol utilized in the present study that healthy individuals increase their heart rate about 10 b/min each minute.

Since the accuracy specifications of both OX under motion conditions was ± 5 b/min, we anticipated that the maximal PR difference between each successive minute to be 15 b/min (+10 b/min for physiological considerations, +5 b/min for accuracy considerations). In contrast, we have observed that some individuals do not increase their heart rate from one minute to the next during the Naughton protocol. Given that the recognized accuracy of the OX PR is ± 5 b/min, it is possible that a properly functioning oximeter could display a

PR 5 b/min lower than the previous min of exercise. Thus, large decreases (20 b/min) in an individual's PR from the previous min of exercise in apparently healthy individuals using this protocol can only be explained as an error. Consequentially, we operationally and prospectively defined a PR 20 b/min less than the preceding minute of exercise as an error. Suspicious PR readings were evaluated by manually taking a radial pulse. Prior to beginning the study we checked both OX's accuracy on resting PR via comparing the OX's reported PR, to PR obtained via manual methodology, and found them to be at unity. Suspicious SaO₂ readings during exercise were identified by noting a drop in SaO₂ ≥ 4% of rest phase SaO₂, or by noting SaO₂ values less than 92% (1).

Statistical Analyses

Data were analyzed via SPSS software version 9.0 (SPSS, Inc., Chicago, IL). The level of significance chosen for all tests was $p < 0.05$. SaO₂ and PR data for both OX under non-motion (rest plus recovery) and motion (sub-maximal exercise) conditions were found to be normally distributed. Pearson correlation coefficients were calculated for SaO₂ and PR for both non-motion and motion conditions. Suspicious PR readings were analyzed using an independent samples t-test (assuming unequal variances) to determine if the mean number of errors were statistically different.

RESULTS

Correlation coefficients for the parameters SaO₂ and PR are presented in Table 2. The mean number of suspicious readings for non-motion (rest plus recovery phase) and motion (sub-maximal exercise) are illustrated in Figure 1. The mean value for the Oxi-Reader suspicious exercise PR readings was 63.7 ± 10.8 b/min while the corresponding mean PR value for the N-395 was 108.9 ± 15.3 b/min. These values were statistically different ($p < 0.001$).

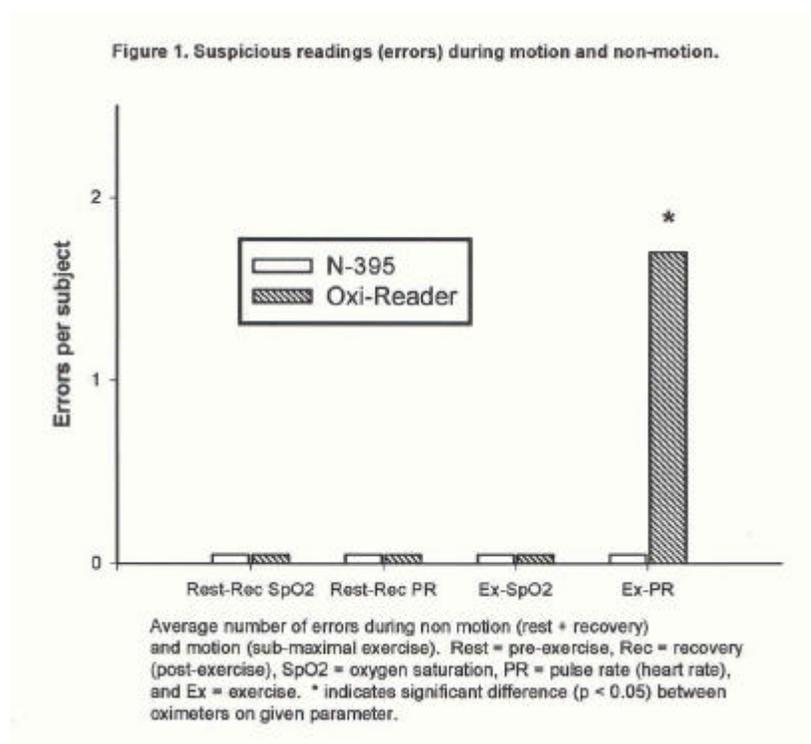
DISCUSSION

The purpose of this study was to determine the effect of motion on SaO₂ and PR readings from the N-395 and the Oxi-Reader. The results demonstrated strong correlations between OX on SaO₂ and PR readings under non-motion and motion conditions (Table 2). However, the correlation between the two instruments on PR was weaker under motion (non-motion, $r=0.981$; motion, $r=0.485$) conditions. The cause of the weaker correlation under motion conditions was the inability of the Oxi-Reader to consistently determine PR (Figure 1) during motion. The Oxi-Reader had no suspicious PR readings under non-motion conditions, but averaged 1.7 suspicious PR readings per subject during sub-maximal exercise. The mean PR value for the Oxi-Reader suspicious PR readings during sub-maximal exercise was 63.7 ± 10.8 b/min. The corresponding mean PR value for the N-395 was 108.9 ± 15.3 b/min.

An illustrative case of the problems experienced with the Oxi-Reader PR values is presented in Figure 2. It is important to note that during the non-motion (rest, min 0-2; recovery, min 14-16) intervals, the Oxi-Reader and N-395 PR values were virtually identical and produced PR readings that were reasonable and physiologically

Table 2. Pearson correlations between oximeters.

Condition	PR	p	SaO ₂	p
Rest and Recovery	0.98	0.0001	0.663	0.0001
Exercise	0.485	0.0001	0.708	0.0001



expected. That is, resting PR was within normal limits (60-100 b/min) and recovery PR values were, as was expected, slightly higher than before exercise (1). However, during exercise the Oxi-Reader produced physiologically unrealistic PR values. Oxi-Reader exercise values were frequently lower (min 6-11) than resting values. These bizarre PR values in healthy volunteers were obviously erroneous. However, intermittently (min 2-4, and 11-14), the Oxi-Reader PR exercise values made physiologic sense and compared favorably with the N-395 readings. In contrast to the Oxi-Reader PR values, the N-395 PR values were reasonable and expected throughout the entire test. The N-395 demonstrated normal PR values during the rest period, an increase in PR values with increasing exercise intensity, and expected physiological recovery values.

Throughout the test (Figure 2) both OX demonstrated virtually identical physiologically predictable SaO₂ values

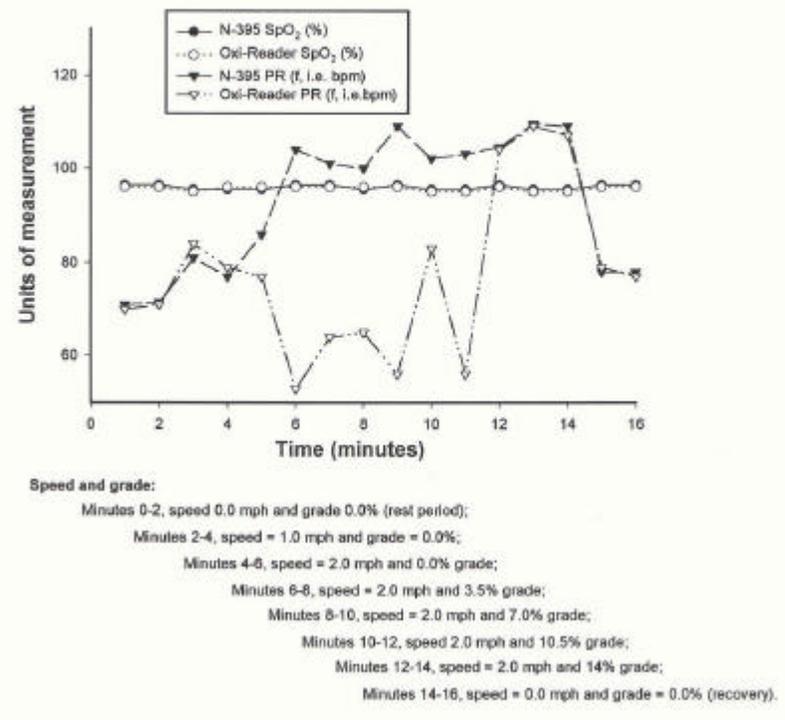
(1). Since the Oxi-Reader OX did not report bizarre SaO₂ values with exercise, exhibit a loss of signal acquisition with exercise, or have bizarre SaO₂ or PR values under non-motion conditions, we suspect that the Oxi-Reader PR artifact algorithm for determining PR in the presence of motion is at fault.

Although we did not prove that the Oxi-Reader PR motion artifact algorithm was flawed, we can rule out some possible causes for the inconsistent and inaccurate Oxi-Reader exercise PR values. One possible source could have been optical interference from the N-395. Optical interference from the N-395 seems unlikely since the Oxi-Reader did not demonstrate any suspicious PR readings during non-motion (either rest or recovery) conditions. Also, since the N-395 probe was taped on the subject with non-translucent tape, it should not have been possible to interfere with the Oxi-Reader. Furthermore, if the suspicious PR readings were caused by optical interference, the SaO₂ performance would seem to have been adversely affected, but it was not. Finally, prior to performing this study, the Oxi-Reader manufacturer recommended that a single finger (middle finger) between the two OX probes would provide adequate shielding to avoid optical interference from the other OX. Others have used similar finger probe placements without optical interference (2,3).

It might be suggested that the cause of the suspicious PR readings was that the N-395 probe, a more expensive reusable probe, was unfairly compared to the Oxi-Reader's inexpensive disposable probe. However, an adhesive disposable probe is recommended for exercise testing by both OX manufacturers to reduce problems of motion artifact. Thus, the N-395 reusable probe (non-adhesive) was at a disadvantage for motion artifact. Taping the N-395 probe into position seemed to eliminate this situation.

Ideally, the response times of both OX should have been identical (11,12,13). However, this was not possible due to design differences of the two OX. The N-395's response time is set by the manufacturer to an automatic

Figure 2. Illustrative case of suspicious pulse readings during exercise.



mode where averaging time is variable. Based on discussion with Nellcor, it is probable that response time of these subjects was close to seven seconds, but could have been as long as ten seconds in some subjects. In contrast, the Oxi-Reader response time was user set to six seconds. A short response time is preferred in dynamic exercise situations. Thus, under progressive exercise conditions, even if both OX were performing ideally, there would be small discrepancies in the data. However, when testing normal subjects using a low intensity protocol, it is unlikely that PR values due to averaging differences would be appreciable.

Similar to the response time setting, the sensitivity setting (used to augment signal acquisition under low perfusion conditions) of both OX should have been the same (11,12,13). However, the N-395 sensitivity setting is not user selectable and is automatically adjusted. In contrast, the Oxi-Reader sensitivity setting was set to the “normal” setting since apparently healthy subjects should have normal finger perfusion. Setting the Oxi-Reader to the “increased sensitivity” mode may have improved its PR performance. Alternatively, setting the Oxi-Reader to the increased sensitivity mode might have made it more susceptible to motion artifacts, resulting in more erroneous PR values. In summary, in lieu of optical interference, finger-probe discrepancies, slightly different averaging times and sensitivity settings not likely being the source of the Oxi-Reader’s PR errors, we suspect that the Oxi-Reader’s artifact algorithm used to determine PR is flawed.

There were two major limitations in this study. The first limitation was that we did not perform test-retest (reliability) measurements. Neither manufacturer provided this information, nor were we able to find an investigation in our literature review which had evaluated reliability in these OX. Thus, the findings of the present study should be interpreted with caution. The second major limitation was that we did not compare the accuracy of either OX to SaO₂ or PR to a true criterion standard (7,11). That is, there were no comparisons of the OX SaO₂ values to arterial oxygen saturation, or PR values compared directly to EKG (heart rate). However, as illustrated in Figures 1 and 2, the Oxi-Reader frequently demonstrated PR errors which are physiologically bizarre and of such magnitude that EKG analyses was not necessary for us to reach the conclusion that the Oxi-Reader exercise PR values were inaccurate under motion conditions. In lieu of the two limitations, we believe a follow-up study is needed, using EKG and arterial blood gas determinations of SaO₂, and test-retest design, to quantify Oxi-Reader’s performance under exercise conditions.

CONCLUSION

In conclusion, the findings of this investigation suggest that under the conditions tested; 1. There was no difference between the two OX on SaO₂ readings under motion or non-motion conditions, 2. The N-395 gave reasonable values on PR at rest and during sub-maximal exercise, and 3. The erroneous Oxi-Reader PR values were of such frequency and magnitude that in exercise applications an alternative form of PR measurement is required. We recommend that other investigators, who have EKG and arterial blood gas technology available, more critically evaluate the Oxi-Reader under exercise conditions.

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ACKNOWLEDGMENTS

Funding for this project was provided by a Research Council Grant, University of Missouri-Columbia, Columbia, MO 65211.

REFERENCES

1. Wasserman, K., Hansen, J., Sue, D., Casaburi, R., Whipp, B. *Principles of exercise testing & interpretation*, 3rd ed. Lippincott Williams and Wilkins; 1999: 124-5, 143-62, 218-40, 349-455.

2. Barker S., Shah N. The effects of motion on the performance of pulse oximeters in volunteers. *Anesthesiol* 1997; 86:101-8.
3. Kehlet C., Rosenberg J. Comparison of the Nellcor n-200 and n-300 pulse oximeters during simulated postoperative activities. *Anaesthes* 1997; 52:450-2.
4. Elfadel I., Weber W., Barker S. Motion-resistant pulse oximetry. *J Clin Monitor* 1995; 11:262.
5. Rheineck-Leyssius A., Kalkman C. Advanced pulse oximeter signal processing technology compared to simple averaging: effect on frequency of alarms in the operating room. *J Clin Anaesthes* 1999; 11:192-5.
6. Carone M., Patessio A, Appendini L., Purro A., Czernicka, Zanaboni S., Donner C. Comparison of invasive and noninvasive saturation monitoring in prescribing oxygen during exercise in copd patients. *Eur Respir J* 1997; 10:446-51.
7. Wood R., Gore C., Hahn A., Norton K., Scroop G., Campbell D., Emonson D. Accuracy of two pulse oximeters during maximal cycling exercise. *Austral J Sci Med* 1997; 29:47-50.
8. Heyward, V. *Advanced fitness assessment exercise prescription*. Burgess Publishing; 1998: 48-78.
9. American College of Sports Medicine. *ACSM's Guidelines for exercise testing and prescription*, 6th ed. Lippincott Williams and Wilkins; 2000: 22-9, 62-4, 68-80, and 92-130.
10. Naughton, J., Balke, B., Nagle, F. Refinements in method of evaluation and physical conditioning before and after myocardial infarction. *Am J Cardiol* 1964, 14: 837-43.
11. Trivedi N., Ghouri A., Lai E., Shah N., Barker S. Pulse oximeter performance during desaturation and resaturation: a comparison of seven models. *J Clin Anaesthes* 1997; 9:184-8.
12. Rheineck-Leyssius A., Kalkman C. Influence of pulse oximeter settings on the frequency of alarms and detection of hypoxemia. *J Clin Monit* 1998; 14:151-6.
13. Farre R., Montserrat J., Ballester E, Hernandez L., Rotger M., Navajas D. Importance of the pulse oximeter averaging time when measuring oxygen desaturation in sleep apnea. *Sleep* 1998; 21:386-90.