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Performance of Wrist-Worn Pulse Oximeter for the Screening of Obstructive Sleep Apnea

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Abstract

Introduction:

A sleep apnea monitor (BM2000A) is a wrist-worn device that measures oxygen saturation and pulse rate during sleep. This study aimed to evaluate the efficacy of the watch-like BM2000A for screening obstructive sleep apnea (OSA).

Materials and Methods:

102 patients complaining of sleep breathing disorders were included; 81% were men and 19% were women. All participants underwent overnight simultaneous polysomnography (PSG) and BM2000A sleep monitoring. The number of apneas and hypopneas, apnea-hypopnea index (AHI), percentage of time spent with oxygen saturation under 90%, average oxygen saturation, lowest oxygen saturation, and duration of sleep were computed by the BM2000A and PSG. Then, these parameters were compared to validate the BM2000A.

Results:

All parameters, measured with BM2000A, had a good correlation ($r \geq 0.6$, $p < 0.0001$) with PSG-derived indexes, except for sleep time ($r = 0.19$, $p = 0.061$) and hypopnea index ($r = 0.4$, $p < 0.0001$). AHI had the strongest correlation ($r = 0.87$, $p < 0.0001$). The mean difference between AHI values calculated with PSG and wrist-worn pulse oximeter (WPO) was -17.66 events/h (95% CI: -50.39 to 15.06). In AHI ≥ 5, BM2000A had 90.7% sensitivity, 100% specificity, 91.2% accuracy, and 0.994 area under the curve. Using AHI ≥ 5, ≥ 15, and ≥ 30 as the screening criteria, optimal WPO-AHI cutoffs to improve the screening accuracy were 3.10, 8.92, and 13.05.

Conclusions:

BM2000A-derived results properly correlate with PSG and can provide OSA screening with good sensitivity and specificity.

Keywords: BM2000A; Home sleep apnea testing; Obstructive sleep apnea; Polysomnography; Wrist pulse oximeter

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Introduction

Obstructive sleep apnea (OSA) is a prevalent chronic respiratory problem associated with sleep (1). OSA occurs with repeated events of upper airway obstruction with or without oxygen desaturation during sleep (2). Apneic attacks mainly terminate with arousal, sympathetic activation, increased blood pressure and pulse rate, re-oxygenation, and release of the inflammatory factors (3).

The global prevalence of OSA has been estimated at 936 million adults aged 30-69 years (men and women) with mild to severe OSA and 425 million adults aged 30-69 years with moderate to severe OSA (4). In a current systematic review by Senaratna et al. (1), the overall prevalence for patients older than 18 years ranged from 9% to 38% and was higher in men when apnea-hypopnea index (AHI) ≥ 5 events/hour was used as the cutoff value for screening moderate and severe OSA. With AHI ≥ 15, the prevalence ranged from 6% to 17% and was much higher in elder groups. The prevalence increased with age; in some elderly groups, it was about 90% in men and 78% in women. Moreover, in a study by Young et al. (5), they estimated that 93% of women and 82% of men with moderate to severe OSA were not diagnosed. These data suggest the high prevalence of OSA with poor public awareness of the disease.

Patients with OSA have a higher risk for various comorbidities such as atrial fibrillation, cardiovascular disease, stroke, chronic kidney disease, hyperlipidemia, diabetes, cancer, anxiety, epilepsy, headache, depression, and cognitive decline in old ages (2,3,6–10). It is necessary to diagnose and treat the condition with available therapies, including behavioral modification (avoiding alcohol and sedatives), losing weight, continuous positive airway pressure (CPAP), oral appliance therapy (orthodontic or mandibular advancing devices), and surgical procedures (tracheostomy and uvulopalatopharyngoplasty) as soon as possible to prevent such complications (11,12).

Screening for OSA is conventionally based on sleep history, review of symptoms, and physical examination including airway examination. The Epworth Sleepiness Scale and STOP-BANG questionnaire are also helpful screening tools for planning for further workups (2).

Four sleep monitoring devices have decreasing sensors of type I towards IV. Type I or polysomnography (PSG) consists of 7 channels, including electroencephalogram (EEG), electrooculogram, electromyogram, electrocardiogram, pulse oximetry, airflow, and respiratory effort with video monitoring, which is used to monitor physiologic parameters during sleep in the clinic (not portable). Type II has the same leads as type I, except that it is portable and needs no technician assistance. Type III and Type IV have fewer sensors, with heart rate and oxygen saturation (SpO_2) being the only inputs for type IV. The gold standard for diagnosing OSA is type I sleep monitoring, and type IV is not recommended due to the lack of measurements and low sensitivity (13,14). Lack of EEG and inability to detect hypopneas related to brain arousals are major challenges of type III and IV sleep monitoring devices that lead to underestimation of the patients with OSA. In addition, there is no airflow measurement in type IV devices (15). Type II, III, and IV sleep monitors are called Home Sleep Apnea Testing (HSAT). As mentioned, there are different types of monitors. Costs, patient preference, feasibility, insurance coverage, and integration with the sleep-analysis system are major factors to consider when choosing the type of technology in practice (13,14).

According to a systematic review by Jonas et al. (14), the sensitivity and specificity for HSAT monitors when using PSG-AHI ≥ 5 as the diagnostic threshold varies from 65 to 100 and 35 to 100, respectively. Moreover, when detecting patients with AHI ≥ 15, the sensitivity ranges from 7 to 100, and the specificity from 15 to 100.

With the development of technology and patients' preferences, wearable sleep monitoring devices or watch-like monitors are more widely used in clinics and research. For example, a study by Xu Y et al. utilized a wearable intelligent sleep monitor (WISM) that monitors heart rate, oxygen saturation, and body movement signals (16). Another study by Misteretta A et al., utilized Embletta MPR as the sleep monitoring device for post-adenotonsillectomy children suffering from OSA (17).

In this study, we compared sleep apnea monitor BM2000A with polysomnography. BM2000A is a lightweight (50 g) wrist-worn pulse oximeter (WPO) that is easy to use, like a watch at home and in clinics for long-term

monitoring. This type IV sleep monitor measures oxygen saturation and pulse rate during sleep, stores these data, and transmits them to a software APP via Bluetooth. Then, the APP analyzes the data from oxygen saturation and pulse rate and gives reports regarding AHI, apnea index (AI), hypopnea index (HI), percentage of time spent with oxygen saturation under 90% (T90%), average oxygen saturation (mean O2), lowest oxygen saturation (min O2), and duration of sleep. These reports can assist the physician in screening obstructive sleep apnea-hypopnea syndrome and managing further therapy.

Materials and Methods

Participants and study design

This screening accuracy study was performed from January 2021 to January 2023. Ethical approval for this study was obtained from the local ethics committee (IR.TUMS. MEDICINE.REC.1401.741), which also complies with the declaration of Helsinki. All patients were informed about the purpose of our research, and informed written permission was obtained from them. We included 102 patients (81% men and 19% women) who visited our hospital for sleep breathing disorders and snoring during sleep. The mean age of participants was 40.5 years. The exclusion criteria were age younger than 18 and unstable health conditions such as uncontrolled cardiovascular or respiratory diseases. We gathered demographic information, including gender, age, and body mass index (BMI), prior to the sleep monitoring session, as mentioned in Table 1. Besides, some individual factors like smoking, underlying disease, medication use, and psychiatric disease were also obtained, and patients with uncontrolled ones were excluded before the sleep monitoring. No questionnaire was used before the sleep monitoring.

Conducting sleep monitoring

Patients underwent an overnight sleep monitoring session at the clinic using simultaneous Lowenstein MiniScreen PRO (Heinen und Löwenstein Inc., Germany) as the PSG device and BM2000A as a portable monitoring. All PSG sensors were attached to the patients, and pulse oximeters of PSG and BM2000A were placed on different hands. Qualified technicians conducted the sleep monitoring at the clinic, but the device has not been taken to the patient's home. Since the patient is being video-monitored during the PSG, a camera was used during the sleep monitoring session. Based on the sleep situation and requirements advised by the company, the minimum time usage of the device is about 6 hours. We advised patients not to sleep during the test day and not to drink beverages that could affect their sleep, like alcohol, coffee, and tea. The version 2.5 of the AASM scoring manual (18) defines apnea as the cessation of respiratory airflow and hypopnea as a decrease in respiratory airflow of $\geq 30\%$ (associated with $\geq$ 3% oxygen desaturation or arousal) for at least 10 seconds used by the competent sleep medicine fellowships to assess the PSG and BM2000A results and make a diagnosis.

We used the watch-like sleep apnea monitor BM2000A as an HSAT device that monitors the oxygen saturation and pulse rate. As previously mentioned, the raw data are stored in the watch and then transmitted to a software app, where the inputs of oxygen saturation and pulse rate are interpreted into some indexes by the automatic machine learning algorithm, including apnea, hypopnea, AHI, T90%, mean O2, min O2, and total sleep duration. Since this device is in the category of black boxes, the company has not provided exact algorithm. Eventually, we compared the parameters generated by BM2000A with the values measured with PSG.

Statistical analysis

Data were analyzed using SPSS Statistics 26.0.0.0 software (IBM Corp, Armonk, NY, USA). Classification and regression trees (CART) were analyzed using Minitab 19.2020.1 software (Minitab, Inc, State College, PA, USA). Normally distributed variables are presented as mean ± standard deviation (SD), and variables without normal distribution are presented using median and interquartile range (IQR).

The correlation between WPO and PSG was tested using the Pearson correlation for normally distributed data and the Spearman correlation for non-normally distributed data. Linear, quadratic, and cubic regressions were run on the WPO and PSG results to determine the fittest model for each parameter.

To check for differences between WPO and

PSG values, a paired sample t-test was used for normally distributed data; for data without normal distribution, a Wilcoxon signed-rank test was performed if the symmetry assumption was met, and a Sign test was done on non-symmetrically distributed data. Additionally, the Bland-Altman analysis was done to validate the agreement between WPO and PSG.

Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated using PSG-AHI thresholds of ≥ 5, ≥ 15, and ≥ 30. Besides, Cohen's kappa coefficient was used to test the consistency of the two methods. Receiver operating characteristic (ROC) curves were plotted for all three diagnostic thresholds to determine the best cutoffs for WPO-AHI. The CART machine algorithm was applied to confirm the manually identified cutoffs. The threshold for statistical significance was *p*-value ≤ 0.05 for all analyses of this study.

Results

Demographics

One hundred two participants were monitored with simultaneous PSG and WPO during an average sleep of 338.2 ± 59.7 minutes. Participants were predominantly male (81.4%), either overweight (41.2%) or obese (44.1%) with a mean BMI of 29.4 ± 4.7, and had severe OSA (60.8%). Table 1 demonstrates participants' characteristics.

Table 1: Participants' characteristics

Characteristics	N=102
Age (year)	40.48 ± 8.94
BMI (kg/m^2)	29.39 ± 4.66
Gender (n, %)	
Male	83 (81.4%)
Female	19 (18.6%)
OSA severity (n, %)	
Non-OSA	5 (4.9%)
Mild OSA	9 (8.8%)
Moderate OSA	26 (25.5%)
Severe OSA	62 (60.8%)

Data are shown as mean ± standard deviation (SD). OSA: obstructive sleep apnea; BMI: body mass index.

Concordance between WPO and PSG

Table 2 summarizes the correlation coefficients between the main parameters observed in PSG and WPO, and fit test regressions.

Table 2: Concordance between the parameters observed simultaneously by PSG and WPO

Parameter	PSG	WPO	Error range	ICC	Correlation coefficient (spearman *r*)	Best fitted model
AHI	37.4 (21.4–62.98)	22.63 (9.49–37.86)	23.1	0.742*	0.87*	linear
AI	44.5 (9.5–315.5)	65 (19–143.25)	195.4	0.706	0.77*	Cubic
HI	144 (75–227)	52 (29–73.75)	151.1	0.205*	0.40*	Quadratic
Mean O_2	93 (91–94)	94.1 (93.09–95.59)	33.2	0.038*	0.61*	Quadratic
T90%	6.25 (0.4–22.7)	1.8 (0.07–6.52)	52.8	0.287*	0.79*	Cubic
Min SpO2	78 (69–82)	85 (83–88)	10.6	0.437*	0.65*	Linear
Sleep time	343.6 (297.85–381.35)	250.5 (154–332)	155.7	0.184*	0.19	Quadratic

AHI: apnea-hypopnea index; AI: apnea index; HI: hypopnea index; Mean O_2: average oxygen saturation; Min O_2: lowest oxygen saturation; T90%: percentage of time spent with oxygen saturation < 90% . *Statistically significant (*p*-value ≤ 0.05).

Of all the variables, the AHI measured by WPO strongly correlated with the PSG-AHI (Spearman $r = 0.87$, $p < 0.0001$). There was also a good correlation (Spearman $r \geq 0.6$, $p < 0.0001$) between values generated by WPO and PSG for each other parameter, except for the hypopnea index with a relatively poor correlation (Spearman $r = 0.4$, $p < 0.0001$) and sleep time (Spearman $r = 0.19$, $p = 0.061$).

The main parameters observed with WPO and PSG are summarized in Table 2. WPO significantly underestimated AHI by -17.66 events/h ($p < 0.0001$); however, the intraclass correlation coefficient was 0.742, indicating good consistency between the two methods. There was also moderate agreement (ICC = 0.706) between the apnea index of WPO and PSG with no statistically significant difference

(155.88 ± 194.88 vs 97.00 ± 98.73, $p = 0.484$). The measured values for other parameters, including hypopnea index, mean O2, T90%, min O2, and sleep time, were different ($p < 0.0001$) and poorly reliable (ICC < 0.5).

The Bland-Altman analysis of PSG-AHI and WPO-AHI showed a mean difference of -17.66 events/h, with limits of agreement ranging from -50.39 to 15.06 events/h (figure 1-a). The difference was not normally distributed and was related to the magnitude of AHI. Therefore, the Bland-Altman plot was transformed by converting the absolute difference into a percentage of the average AHI, which revealed a mean difference of -58.16% and -138.12% to 21.80% limits of agreement (figure 1-b).

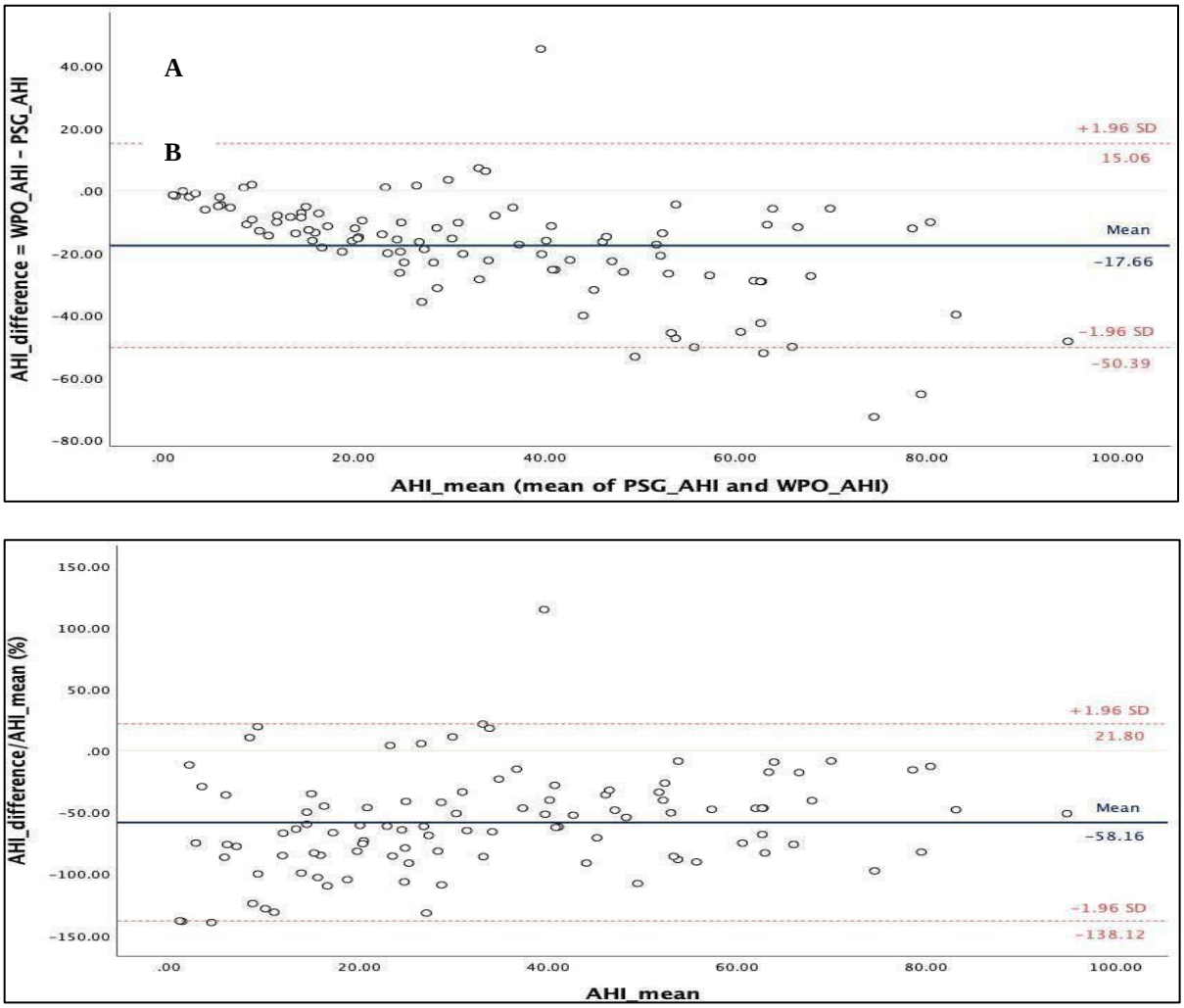

Fig 1: a: Bland-Altman plot of AHI measured with PSG compared to WPO-AHI. b: Transformed Bland-Altman plot of PSG-AHI in comparison to WPO-AHI. AHI: apnea-hypopnea index; PSG: polysomnography; WPO: wrist pulse oximeter.

Screening efficiency of WPO

Table 3 shows sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), positive likelihood ratio (LR+), negative likelihood ratio (LR-), accuracy, and area under the curve (AUC) of WPO in screening OSA at different AHI thresholds. The specificity was high (≥ 90%) using either of the thresholds to identify OSA, while the sensitivity was high (≥ 90%) only with AHI ≥ 5 and was lowered when using higher thresholds. The accuracy of WPO for AHI ≥ 5, AHI ≥ 15, and AHI ≥ 30 was 91.2%, 75.5%, and 72.5%, respectively. According to the kappa coefficients of agreement shown in Table 3, the screening outcome of WPO for all three thresholds is moderately ($0.4 < \kappa \leq 0.6$) concordant with PSG.

Table 3: Screening performance of WPO at different apnea-hypopnea indices

	Number of participants	Sen (%)	Spe (%)	PPV	NPV	LR+	LR-	Accuracy	AUC	*κ*
AHI ≥ 5	97	90.7	100	100	35.7		0.09	91.2	0.994	0.489
AHI ≥ 15	88	71.6	100	100	35.9		0.28	75.5	0.978	0.409
AHI ≥ 30	62	59.7	92.5	92.5	59.7	7.96	0.44	72.5	0.925	0.475

AHI: apnea-hypopnea index; AUC: area under the curve; LR: likelihood ratio; NPV: negative predictive value; PPV: positive predictive value; Sen: sensitivity; Spe: specificity

ROC analysis showed that the best cutoff value for WPO-AHI to identify patients with mild OSA (AHI ≥ 5) was 3.10. With WPO-AHI ≥ 3.10, the device can reach 99% sensitivity and 100% specificity with a 0.994 area under the ROC curve. Using AHI ≥ 15 as the criterion for screening OSA and 8.92 as the optimal cutoff value, screening efficiency reduced to 92% sensitivity, 92.9% specificity, and 0.978 AUC. Screening efficiency decreased even more when a threshold of AHI ≥ 30 was used, and the most suitable cutoff was 13.05, with 96.8% sensitivity and 82.5% specificity (figure 2).

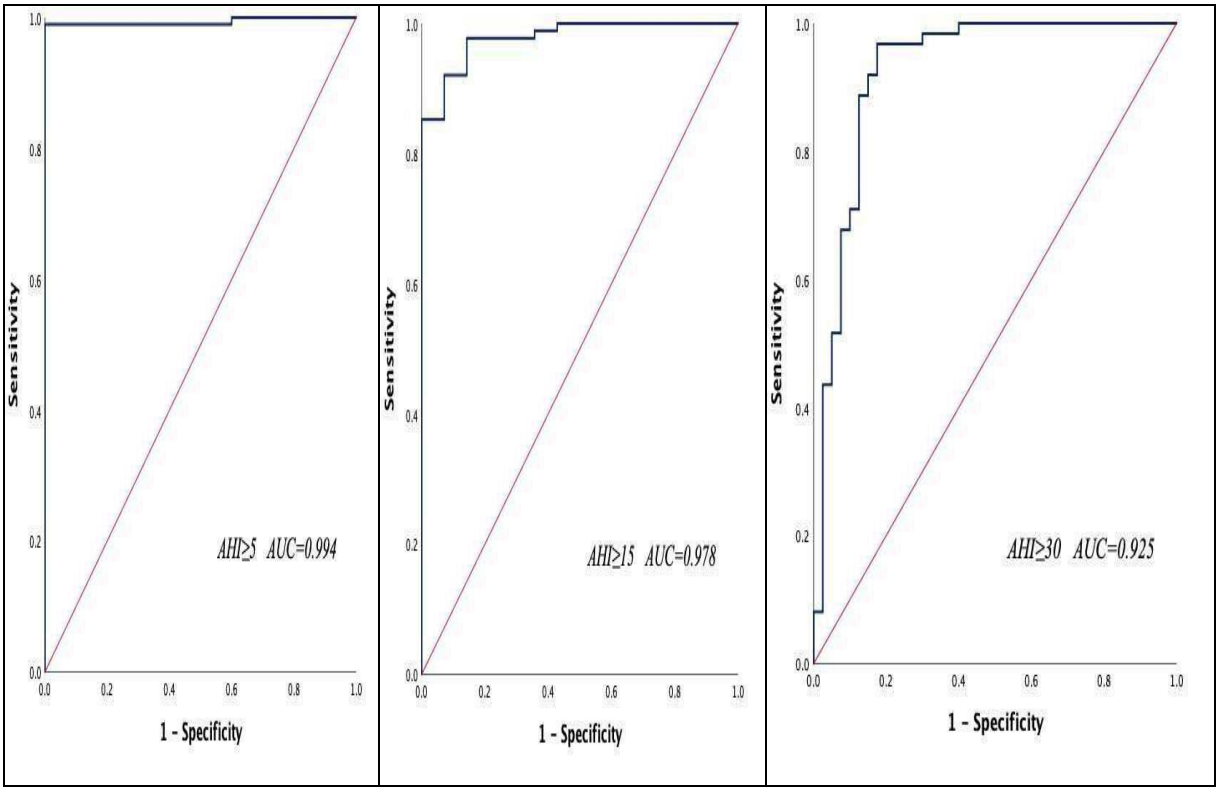

Fig 2: ROC curves for screening OSA with WPO using three different thresholds. AHI: apnea-hypopnea index; AUC: area under the curve; OSA: obstructive sleep apnea; PSG: polysomnography; ROC: receiver operator characteristic; WPO: wrist pulse oximeter.

Table 4 demonstrates the classification of participants by WPO against the actual grading by PSG. Forty-seven cases (46.08%) were correctly classified using WPO. The device notably underestimated the severity of OSA since 52 participants (50.98%) were classified as one or two classes lower than their actual. Only 3 participants with moderate OSA (2.95%) were overestimated as severe. CART analysis was applied to fit better classification thresholds for the AHI of WPO. AHI of ≥ 3.10, ≥ 5.86, and ≥ 13.05 were found as the criterion for staging OSA using the BM2000A (figure 3).

Table 4: The confusion matrix for OSA staging by PSG and WPO based on standard thresholds.

	Without OSA	Mild OSA	Moderate OSA	Severe OSA
Without OSA	5	0	0	0
Mild OSA	7	2	0	0
Moderate OSA	2	18	3	3
Severe OSA	0	5	20	37

WPO estimated stage of OSA

AHI: apnea-hypopnea index; OSA: obstructive sleep apnea; PSG: polysomnography; WPO: wrist pulse oximeter

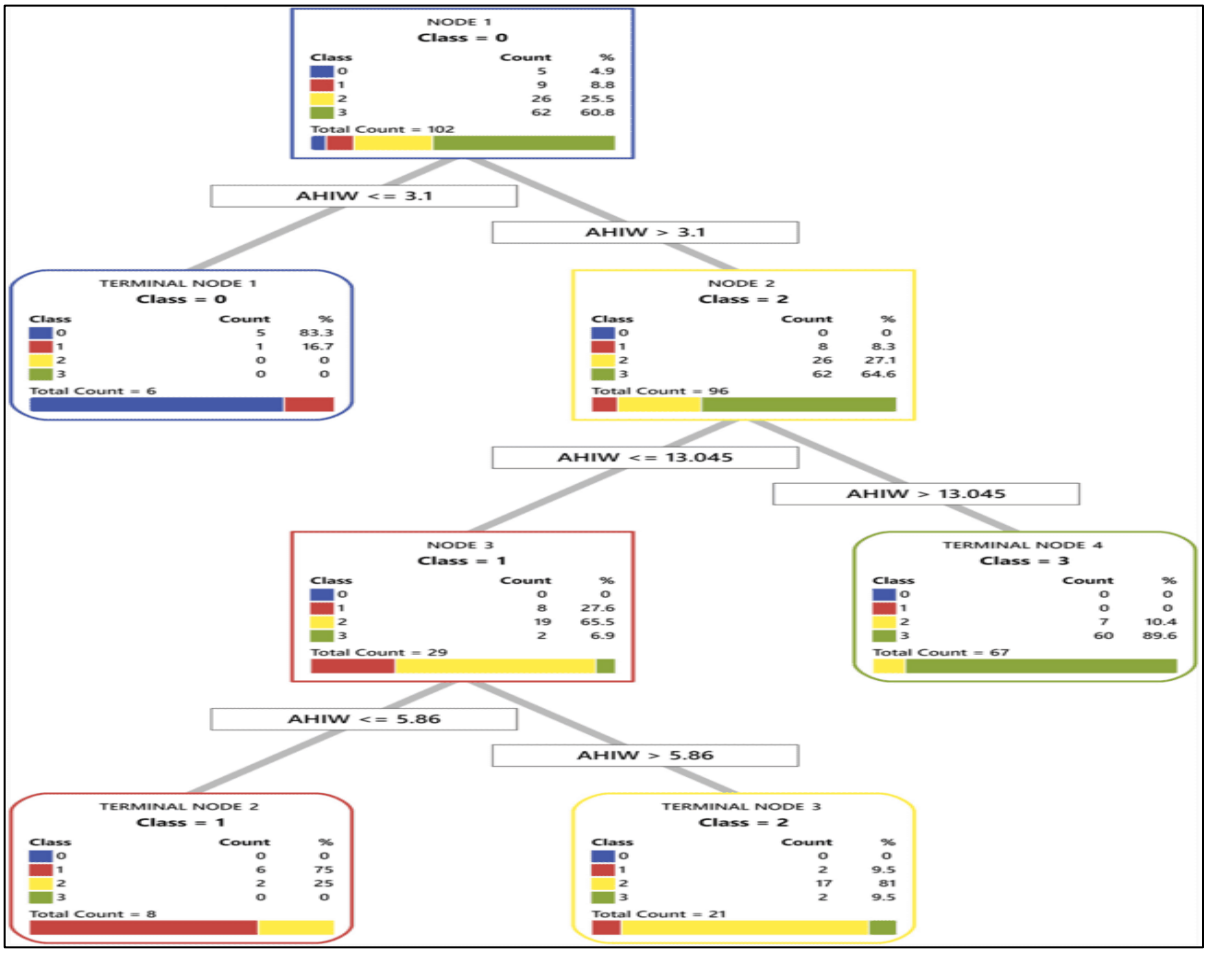

Fig 3: CART optimal tree diagram to improve classification accuracy. AHIW: apnea-hypopnea index of wrist pulse oximeter; CART: classification and regression tree.

Discussion

BM2000A is a wrist-worn pulse oximeter utilized as an HSAT device for screening and assessment of OSA. Our study evaluated the accuracy of the BM2000A compared to simultaneous PSG as the gold standard. The results demonstrated that the wrist-worn pulse oximeter BM2000A shows good screening efficiency in identifying patients with OSA of various severities. Using AHI $\geq$ 5 as the screening threshold, WPO detects OSA with 90.7% sensitivity, 100% specificity, and 91.2% accuracy. The performance of BM2000A is also satisfying in measuring oxygen

desaturation parameters, including AHI, AI, HI, T90%, mean O2, and min O2. The values of these parameters generated by WPO had moderate to strong correlation (spearman $r \geq 0.6$) with actual values measured with PSG. AHI had the strongest positive correlation (spearman $r = 0.87$); however, it was significantly underestimated by WPO compared to PSG (25.66 ± 18.74 events/h vs. 43.33 ± 27.79 events/h, $p < 0.0001$). Total sleep time was the only non-oxygen-related parameter measured with WPO, which was poorly correlated with PSG values.

The positive correlation between respiratory event index (REI) recorded by type IV sleep monitor and PSG- derived AHI was found in other portable oximetry-based monitors. Watch-PAT and Circul oximetry studies have reported a high level of concordance between PSG and wearable-monitor assessment of AHI (19,20). Regarding AHI measurement bias, Circul and WISM also reported underestimating AHI by 3.2 and 6.8 events/hour, respectively (16,20). The underestimation of PSG-AHI by oximetry-based monitors may be related to how respiratory events are defined. a decrease in SpO2 does not necessarily accompany apnea and hypopnea in PSG , while it is the only signal for WPO to detect respiratory events. Interruption of breath for 10 seconds or more with no oxygen saturation reduction recorded by airflow signals would be scored as apnea in PSG. Type of hypopneas with arousals but no desaturations would also be missed since there is no electroencephalogram signal on WPO to detect arousals (21). Furthermore, respiratory events coupled with movements could remain undetected due to automatic algorithms incorrectly discarding low-quality signals (20). ROC curves were further used to demonstrate the screening performance of WPO. The AUC representing the accuracy of WPO was decreased when using higher thresholds of AHI. With a threshold of AHI ≥ 5 for screening OSA, WPO can reach 90.7% sensitivity and 100% specificity with an AUC of 0.994. However, when screening moderate-severe patients with AHI ≥ 15, the sensitivity of WPO was lowered by 20% (71.6%) with no change in specificity (100%). Using AHI ≥ 30 as the threshold, WPO displayed 59.7% sensitivity and 92.5% specificity (AUC = 0.925). Compared to other HSAT devices, WPO showed good performance, as detailed in Table 5. In Zhao et al. pilot study (20), Circul oximetry revealed 87% sensitivity and 83% specificity for an AHI threshold of ≥ 5 as well as 66% sensitivity and 96% sepcificity using a threshold of AHI ≥ 15. Smartwatch GT2, as Chen et al. reported (22), showed sensitivity and specificity of 76.5% and 100% for AHI ≥ 5 and 85.7% and 100% for AHI ≥ 15, respectively.

The overall specificity of BM2000A was reasonable, while underestimation of AHI by WPO resulted in relatively low sensitivity for all three thresholds. Thus, adjusting WPO-AHI cutoffs to lower values would improve the sensitivity. Using 3.10 events/h as the WPO-AHI cutoff value, the device can reach 99% sensitivity with no change in 100% specificity. When applying WPO in practice, it may be considered to identify OSA-negative or OSA-positive patients. The high sensitivity of WPO in screening patients with AHI ≥ 5 makes it suitable for OSA screening in large populations, leading to promptly identifying and treating this morbid condition. The underestimation of AHI by WPO also caused misclassification when using standard thresholds of AHI ≥ 5, ≥ 15, and ≥ 30, as illustrated by the confusion matrix. The cutoffs estimated by the CART machine learning algorithm for WPO-AHI (3.10, 5.86, 13.05) to improve classification accuracy are the same as modified thresholds manually calculated using ROC curves (3.10, 8.92, 13.05). However, further studies with bigger sample sizes are needed to establish WPO-AHI thresholds to classify patients with OSA in clinical settings.

The small sample size of OSA-negative patients for thresholds of AHI ≥ 5 and ≥ 15 (5/102, 14/102) makes the reliability of 100% specificity for these thresholds doubtful. Nevertheless, the 92.5% specificity of WPO in recognizing severe OSA is conclusive since there was an adequate number of patients with non-severe OSA. So, WPO- AHI ≥ 30 is highly suggestive of severe OSA, which helps to correctly identify high-risk patients and allocate medical resources such as CPAP accordingly.

BM2000A is a comfortable, easy-to-wear monitor that does not require technician support during sleep. Its convenience and lower price (about 60 dollars) compared to other HSAT

devices (200 to 300 dollars) and PSG, makes it a good option for diagnosing high-risk patients and screening for OSA on a large scale. This study has some limitations. Firstly, the study population consists only of patients referred to a sleep clinic with a suspected sleep breathing disorder. Thus, the utility of BM2000A in a general population needs further evaluation. Secondly, the small sample size of participants without OSA or mild OSA makes the recommended WPO- AHI cutoffs relatively unreliable. Therefore, further investigation with a more adequate sample size is suggested. Thirdly, patients aged under 18 were excluded from the study, so the accuracy of WPO measurement for this age group remains to be determined (Table 5).

Table 5: The performance of recently reported HSAT devices for detecting OSA compared to this study

Study	HSAT device	Acquired parameters	AHI threshold	Sen (%)	Spe (%)	AUC
Choi et al., 2018 (19)	Watch-PAT	PAT, SpO2, pulse rate, snoring, wrist motions, and body position	AHI ≥ 5	100	96	
			AHI ≥ 15	80	100	
Chen et al., 2021 (22)	Photoplethysmography-Based Smartwatch	Pulse rate and SpO2	AHI ≥ 5	76.5	100	0.811
			AHI ≥ 15	85.7	100	0.929
Zhao et al., 2022 (20)	Circul Ring pulse oximeter	SpO2, pulse rate, movement, and sleep/wake status	AHI ≥ 5	87	83	0.929
			AHI ≥ 15	66	96	0.940
Xu et al., 2022 (16)	Wearable intelligent sleep monitor (WISM)	SpO2, pulse rate, and body movement signals	AHI ≥ 5	93	77	0.95
			AHI ≥ 15	92	89	0.95
This study	BM2000A wrist-worn pulse oximeter	SpO2, pulse rate	AHI ≥ 5	90.7	100	0.99
			AHI ≥ 15	71.6	100	0.98

AHI: apnea-hypopnea index; AUC: area under the curve; Sen: sensitivity; Spe: specificity; SpO2: oxygen saturation

Conclusion

This study evaluated the performance of the BM2000A in assessing patients with suspected obstructive sleep apnea. Despite the significant underestimation, AHI has a high correlation and agreement compared to simultaneous PSG recording. The high sensitivity of BM2000A when using a threshold of AHI ≥ 5 makes it a feasible method for large scale OSA screening. Considering its high specificity at the screening threshold of AHI ≥ 30, BM2000A can be utilized to rule in patients with severe OSA for further management. This low-price, comfortable, and easy-to-use wrist-worn pulse oximeter provides reliable detection of OSA with good sensitivity and specificity.

Further studies are needed to confirm its utility in community-based population and particular subgroups with obesity or cardiopulmonary comorbidities and to validate appropriate AHI cutoffs dedicated to BM2000A.

Data availability statement

The detailed participant data are available from the corresponding author upon reasonable request.

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Compliance with Ethical Standards

Conflicts of interest

The authors declare no conflicts of interest. All devices were purchased, and the manufacturer left no footprint in the sleep clinic.

Ethical approval:

This study obtained ethical approval for from the local ethics committee (IR.TUMS. MEDICINE.REC.1401.741). The study involving human participants also complied with the Declaration of Helsinki. All patients were informed about the purpose of the research, and informed consent was obtained from the participants.

References

1. Senaratna C V, Perret JL, Lodge CJ, Lowe AJ, Campbell BE, Matheson MC, et al. Prevalence of

obstructive sleep apnea in the general population: A systematic review. Sleep Med Rev. England; 2017;34:70–81. DOI: 10.1016/j.smrv.2016.07.002

2. Rundo JV. Obstructive sleep apnea basics. Cleve Clin J Med. United States; 2019;86(9 Suppl 1):2–9. DOI: 10.3949/ccjm.86.s1.02

3. Ralls F, Cutchen L. A contemporary review of obstructive sleep apnea. Curr Opin Pulm Med. United States; 2019;25(6):578–93. DOI: 10. 1097/ MCP.0000000000000623

4. Benjafield A v, Ayas NT, Eastwood PR, Heinzer R, Ip MSM, Morrell MJ, et al. Estimation of the global prevalence and burden of obstructive sleep apnoea: a literature-based analysis. Lancet Respir Med. 2019;7(8):687–98. DOI: https://doi. org/ 10.1016/S2213-2600(19)30198-5

5. Young T, Palta M, Dempsey J, Skatrud J, Weber S, Badr S. The occurrence of sleep-disordered breathing among middle-aged adults. N Engl J Med. N Engl J Med; 1993;328(17):1230–5. DOI: 10.1056/NEJM199304293281704

6. Lin C-H, Perger E, Lyons OD. Obstructive sleep apnea and chronic kidney disease. Curr Opin Pulm Med. United States; 2018;24(6):549–54. DOI: 10.1097/MCP.0000000000000525

7. Gupta MA, Knapp K. Cardiovascular and psychiatric morbidity in obstructive sleep apnea (OSA) with insomnia (sleep apnea plus) versus obstructive sleep apnea without insomnia: a case-control study from a Nationally Representative US sample. PLoS One. 2014;9(3):e90021. DOI: 10.1371/journal.pone.0090021

8. Palamaner Subash Shantha G, Kumar AA, Cheskin LJ, Pancholy SB. Association between sleep- disordered breathing, obstructive sleep apnea, and cancer incidence: a systematic review and meta-analysis. Sleep Med. Netherlands; 2015; 16(10): 1289–94. DOI: 10.1016/j.sleep.2015.04.014

9. Kirsch DB. Obstructive Sleep Apnea. Continuum (Minneap Minn). United States; 2020; 26(4): 908–28. DOI: 10.1212/CON.000000000000 0885

10. Acker J, Richter K, Piehl A, Herold J, Ficker J, Niklewski G. Obstructive sleep apnea (OSA) and clinical depression—prevalence in a sleep center. Sleep and Breathing. Springer Verlag; 2017; 21(2): 311–8. DOI: 10.1007/S11325-016-1411-3/TABL ES/2

11. Chang H-P, Chen Y-F, Du J-K. Obstructive sleep apnea treatment in adults. Kaohsiung J Med Sci. China (Republic: 1949-); 2020;36(1):7–12. DOI: 10.1002/kjm2.12130

12. Sutherland K, Cistulli PA. Recent advances in obstructive sleep apnea pathophysiology and treatment. 2014; DOI: 10.1111/sbr.12098

13. Rundo JV, Downey R 3rd. Polysomnography. Handb Clin Neurol. Netherlands; 2019;160:381–92. DOI: 10.1016/B978-0-444-64032-1.00025-4.

14. Jonas DE, Amick HR, Feltner C, Weber RP, Arvanitis M, Stine A, et al. Screening for Obstructive Sleep Apnea in Adults: Evidence Report and Systematic Review for the US Preventive Services Task Force. JAMA. United States; 2017; 317(4):415–33. DOI: 10.1001/jama. 2016. 19635

15. Zancanella E, do Prado LF, de Carvalho LB, Machado Júnior AJ, Crespo AN, do Prado GF. Home sleep apnea testing: an accuracy study. Sleep Breath. Sleep Breath; 2022;26(1):117–23. DOI: 10.1007/S11325-021-02372-6

16. Xu Y, Ou Q, Cheng Y, Lao M, Pei G. Comparative study of a wearable intelligent sleep monitor and polysomnography monitor for the diagnosis of obstructive sleep apnea. Sleep Breath. Germany; 2022; DOI:10.1007/s11325-022-02599-x

17. Mistretta A, Modica DM, Pitruzzella A, Burgio S, Lorusso F, Billone S, et al. OSAHS Growth Impairment and Resolution after Adenotonsillectomy in Children. Iran J Otorhinolaryngol. Iran J Otorhinolaryngol; 2022; 34(122): 145–53. DOI: 10. 22038/ IJORL. 2022. 57642.2986

18. Berry RB, Albertario CL, Harding SM, Uoyd RM, Plante DT, Quan SF, et al. The AASM Manual for the Scoring of Sleep and Associated Events RULES, TERMINOLOGY ANO TECHNICAL SPECIFICATIONS VERSION 2.5 AASM Sconng Manual Version 2.5 1.

19. Choi JH, Lee B, Lee JY, Kim HJ. Validating the Watch-PAT for Diagnosing Obstructive Sleep Apnea in Adolescents. J Clin Sleep Med. J Clin Sleep Med; 2018;14(10):1741–7. DOI: 10.5664/ JCSM.7386

20. Zhao R, Xue J, Zhang X, Peng M, Li J, Zhou B, et al. Comparison of Ring Pulse Oximetry Using Reflective Photoplethysmography and PSG in the Detection of OSA in Chinese Adults: A Pilot Study. Nat Sci Sleep. Nat Sci Sleep; 2022;14:1427–36. DOI: 10.2147/NSS.S367400

21. Kapur VK, Auckley DH, Chowdhuri S, Kuhlmann DC, Mehra R, Ramar K, et al. Clinical Practice Guideline for Diagnostic Testing for Adult Obstructive Sleep Apnea: An American Academy of Sleep Medicine Clinical Practice Guideline. J Clin Sleep Med. American Academy of Sleep Medicine; 2017;13(3):479. DOI: 10.5664/JCSM.6506

22. Chen Y, Wang W, Guo Y, Zhang H, Chen Y, Xie L. A Single-Center Validation of the Accuracy of a Photoplethysmography-Based Smartwatch for Screening Obstructive Sleep Apnea. Nat Sci Sleep. Nat Sci Sleep; 2021;13:1533–44. DOI: 10.2147/ NSS.S323286