Getting More from the Sleep Recording

Walter T. McNicholas, MD, FERS

KEYWORDS

- Obstructive sleep apnea • Signal processing • Oximetry • Acoustic recording • Pulse transit time
- Actigraphy • Biosensors

KEY POINTS

- Developments in signal processing facilitate the automated analysis of traditional signals such as oxygen saturation and electroencephalogram, which provides superior insight into physiology and pathophysiology compared to manual analysis.
- These developments have resulted in increasing recognition that the traditional measure of sleep-disordered breathing, the apnea-hypopnea index, is a poor predictor of disease significance.
- New approaches to the recording and analysis of traditional signals such as snoring and oxygen saturation facilitate ambulatory diagnosis of obstructive sleep apnea.
- Detailed insight into the characteristics of oxygen desaturation during sleep provides superior prediction of comorbidities than the apnea-hypopnea index.
- Derivatives of the electrocardiogram and pulse wave provide indirect data on sleep-disordered breathing that are suitable for ambulatory diagnosis.

INTRODUCTION

Sleep recordings have been a feature of clinical sleep practice for more than 4 decades, and full sleep laboratory recordings in the form of polysomnography (PSG) remain largely based on principles established in these early years. Sleep staging remains fundamentally based on the scoring rules established by Rechtschaffen and Kales in 1968,¹ and the scoring of sleep-disordered breathing (SDB) events is based on the so-called Chicago Criteria introduced in 1999, which also proposed a severity grading for obstructive sleep apnea (OSA) based on the frequency of apneas and hypopneas per hour of sleep (AHI).² However, developments in technology and signal analysis in more recent years offer considerable scope to expand and enhance the information that can be obtained from sleep studies, and advances in the understanding of mechanisms contributing to cardiometabolic comorbidities offer new insights regarding the most important sleep-related variables that contribute

to these comorbidities.³ There has been increasing interest among the sleep research community in exploring new and novel approaches to the diagnosis of sleep disorders, especially OSA, and there is increasing recognition that variables such as the AHI may not be the most important measure to quantify the severity of the disorder.⁴

The focus of this review is to explore how additional information may be obtained from signals obtained in traditional sleep recordings such as laboratory-based PSG and home-based sleep studies, as well as information from additional signals that do not form part of traditional sleep studies. The review will focus primarily on the assessment of patients with suspected OSA, as the high prevalence of this disorder, which affects up to one billion subjects worldwide,⁵ makes it particularly relevant to explore novel approaches to the accurate and reliable diagnosis of this disorder in the ambulatory setting.⁶

Currently, disease severity is measured using AHI as determined from a sleep study. However, there is poor association between daytime

Department of Respiratory and Sleep Medicine, School of Medicine, University College Dublin, St. Vincent's Hospital Group, Elm Park, Dublin 4, Ireland
E-mail address: walter.mcnicholas@ucd.ie

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symptoms such as excessive daytime sleepiness and the AHI,⁷ and there is increasing evidence that cardiometabolic comorbidities may be more related to measures of oxygen desaturation during sleep than the AHI.³ Thus, there is increasing interest in moving away from the AHI as the most important measure of OSA severity toward a more personalized approach to OSA diagnosis and treatment,⁸ which considers individual risk factors, clinical history, and comorbid disease in the diagnosis and treatment of each patient with OSA.

INDIVIDUAL PATIENT PHENOTYPING

While overnight diagnostic sleep studies provide the core evidence of SDB in patients with suspected OSA, there is clear evidence that the sleep study alone does not provide sufficient evidence for the diagnosis of the clinical syndrome. This aspect has been recognized for many years,^{9,10} and more recently, there is strong evidence that clusters of different clinical phenotypes can be identified among the broad population of patients presenting for assessment.¹¹ Furthermore, certain pathophysiological traits that are very common in OSA such as loss of nocturnal dipping of blood pressure (BP) have significant implications for the development of associated comorbidity.¹² Thus, whatever sleep study is used in the assessment of suspected OSA, the findings must be integrated into the overall assessment of the patient as regards clinical significance, and management should be linked to the underlying clinical and pathophysiological phenotypes where additional factors to the AHI such as acute systemic effects and associated relevant comorbidity are factored into the decision-making process.⁸ A further consideration in the clinical assessment of OSA is the role of the AHI alone, referred to here in this context as SDB. Although the International Classification of Sleep Disorders refers to AHI ≥ 15 as sufficient for a diagnosis of OSA, this appears questionable in the context of this level of SDB being reported in up to 50% of a normal adult male population.¹³

DEVELOPMENTS IN THE ANALYSIS OF EXISTING SIGNALS

Core signals relevant to sleep and breathing disorders such as airflow, oxygen saturation, and cardiac variables have been included in sleep studies for decades, but developments in signal analysis have permitted enhanced and clinically relevant information to be obtained, which significantly adds to the diagnostic potential of the

studies concerned. Furthermore, novel approaches to the analysis of these traditional signals may facilitate the use of limited diagnostic systems that may be especially useful in the ambulatory setting.

ELECTROENCEPHALOGRAPHY AND SLEEP STAGING

Developments in electroencephalographic (EEG) recording technology have permitted the introduction of ambulatory EEG recordings, which may use a full EEG montage. This technology is not necessary in most clinical situations involved in the assessment of OSA, although some limited ear-based EEG recording systems have been developed that are easy to apply and may provide additional useful information in the ambulatory respiratory-sleep clinical setting.¹⁴

Specialized computer-based analysis of the EEG by techniques such as spectral analysis provides additional insight into sleep physiology and pathology beyond traditional sleep staging, but these are research-oriented and have little application in the clinical setting of respiratory sleep disorders.^{15,16}

ACOUSTIC AND AIRFLOW DEVICES

Acoustic Devices

Although snoring is a common feature in patients with OSA, the symptom has limited value on its own in the assessment of OSA because of its weak relationship with the AHI.¹⁷ Nonetheless, the detailed characteristics of snoring and, especially, the characteristic intermittent nature of snoring in patients with OSA provide potential diagnostic utility both alone and in combination with other signals. In this context, periods of apnea/hypopnea have quite different acoustic characteristics to nonapneic snoring. One such acoustic device is BresDX (BresoTEC Inc, Toronto, Ontario, Canada), which is a portable device that consists of a lightweight face frame, which contains an embedded electronic module and microphone. Recorded sounds are continually stored and can subsequently be downloaded for analysis.^{18,19} As might be expected, a characteristic cyclical intermittent pattern of snoring has the greatest predictive potential for the diagnosis of OSA. In one report of 135 subjects with suspected OSA, the calculated AHI using BresDX showed a relatively good correlation with PSG and demonstrated a diagnostic accuracy ranging between 88.9% and 93.3% at AHI cutoffs of 5 to 15.²⁰ More recently, an over the counter small, wireless wearable patch has been developed

(Zansors, Arlington, VA), which estimates breathing patterns using an inbuilt microphone and includes an accelerometer to record movement. A pilot study of the device demonstrated 75% sensitivity and 71% specificity for detecting SDB compared to gold standard PSG.²¹

Airflow Devices

Devices that record airflow by nasal pressure recordings as a single measure have been developed as a more simple ambulatory diagnostic technique for OSA, and an example of such a device is the ApneaLink (Resmed, Sydney, Australia).²² One report comparing the device with PSG showed a 73.1% sensitivity and 91% specificity for detecting an AHI greater than 15 in at-risk populations,²³ with similar results reported in other studies.^{22,24}

OXIMETRY

Overnight oximetry has long been proposed as a simple and reasonably accurate technique for OSA diagnosis, especially in severe cases,^{10,25} but has limited reliability in mild OSA where oxygen desaturations may be relatively minor. To be useful in the assessment of patients with OSA, arterial oxygen saturation (SpO₂) recordings require a high sampling rate (>0.5 Hz) to ensure detection of the intermittent oxygen desaturations that are characteristic of the disorder. In clinical practice, several relevant variables may be obtained from the recordings, including the oxygen desaturation index (ODI), which is the number of desaturations per hour which drop $\geq 3\%$ (ODI₃) or $\geq 4\%$ (ODI₄) below the baseline level, and the cumulative time with an SpO₂ below a predetermined level, usually 90% (T90). Additional information can be obtained from the SpO₂ variability, referred to as the delta index.^{26,27} In OSA, a “saw-tooth” pattern of recurring transient oxygen desaturations is seen, especially in severe cases, which provides a unique visual picture of the disorder. Simple indices such as the ODI may fail to capture all the important and potentially relevant pathophysiological characteristics²⁵ and novel strategies for the analysis of oximetry using automated techniques^{28–30} to help maximize the diagnostic potential of SpO₂ data. Furthermore, novel approaches to oxygen desaturation such as the hypoxic burden have been demonstrated to provide a superior prediction of cardiovascular morbidity and mortality than the AHI in large-population studies.³¹

Computer-assisted applications that provide automated signal processing facilitate the quantification of the frequency, duration, and severity of desaturations, which enhance the clinical

assessment of OSA.^{29,32–34} Some devices use smartphone-based technology or wearable applications as the receiver which may have potential for home screening to prioritize cases for more detailed investigation^{35–37} and may also have a role in treatment follow-up.³⁸

Oximetry and Apneas and Hypopneas per Hour of Sleep

The ODI may be used as an alternative to the AHI to quantify the number of respiratory events during the night but may underestimate the severity of OSA with potentially important clinical consequences^{39,40} that may influence treatment decisions.²⁶ However, a more detailed analysis of the SpO₂ signal with computer-assisted and machine learning algorithms improves the predictive ability^{41–43} with a diagnostic accuracy of up to 96.7% reported. Furthermore, there is growing evidence that measures of oxygen desaturation are superior to AHI in the prediction of comorbidities including hypertension (HTN),⁴⁴ diabetes mellitus,⁴⁵ and heart failure.⁴⁶

Oximetry may also have value in screening patients for OSA in certain comorbidities including stroke,⁴⁷ heart failure,⁴⁸ morbid obesity,^{49,50} and chronic obstructive pulmonary disease (COPD).⁵¹ In stroke, OSA is associated with diminished recovery and increased mortality.⁵² In patients with congestive cardiac failure, overnight oximetry has a high sensitivity (97%) but poor specificity (32%) for SDB.⁴⁸ Oximetry performs better in patients with gross obesity with reports of up to 100% sensitivity and 93% specificity for SDB in ambulatory testing.⁴⁹ Oximetry has limited potential for the diagnosis of OSA in patients with COPD with low sensitivity (59%) and specificity (60%)⁵¹ although performs better when combined with novel signal analysis technology.⁵³

Cardiac Based Measures

Electrocardiograph (ECG) analysis: monitoring of heart rate variability (HRV), electrocardiograph morphology, and respiration

Monitoring of HRV by overnight ECG has long been recognized as a potential diagnostic tool in patients with SDB.⁵⁴ In standard PSG, a single-lead ECG is recorded to allow measurement of heart rate and rhythm. A special dedicated software program allows analysis of HRV⁵⁵ that can provide information relating to autonomic activity and may give added insight into sleep stages.⁵⁶ Further information can be obtained from fluctuations in the QRS amplitude that are a consequence of rib cage movements during respiration. The

combination of ECG-derived respiratory movement and sleep apnea-related HRV has the potential to be a useful screening tool for OSA⁵⁷ and has the added value of being available in a typical cardiology setting, which provides the potential for screening in this setting before referral to a sleep clinic.

Pulse transit time

The pulse transit time (PTT) is a variable that is derived from the ECG and the arterial pressure wave measured by a finger probe and has been reported to reflect inspiratory effort.⁵⁸ PTT measures the time taken for the arterial pulse wave to travel between the aortic valve (R wave on ECG) and the finger blood vessels as indicated by pulse oximetry. Pulse wave speed varies with arterial stiffness, which in turn is influenced by the BP level. PTT has been reported to give an indirect measure of both apnea and arousal.⁵⁸

Peripheral arterial tonometry (the pulse wave as a measure)

Peripheral arterial tonometry (PAT) provides a detailed assessment of the pulse wave and is reported to be a relatively robust diagnostic screening method for OSA. The pulse wave amplitude is influenced by sympathetic tone, and arousals are also associated with a drop in pulse amplitude. Furthermore, the pulse rate also provides an indirect assessment of sleep stage.⁵⁹ WatchPAT (Itamar Medical, Caesarea, Israel) uses a proprietary algorithm combining PAT data, oxygen saturation, pulse rate, and actigraphy that generates an estimate of total sleep time and calculates an AHI.⁶⁰ WatchPAT has been evaluated in several studies with some, but not all, reports indicating the device to provide a reasonably accurate assessment of OSA.^{59–61} A meta-analysis found a good correlation between sleep indices calculated by laboratory-based PSG and those obtained from a PAT device ($r = 0.889$),⁶² thus supporting its use as a viable ambulatory diagnostic tool for OSA.

Blood pressure monitoring as a potential diagnostic tool

OSA is a recognized independent risk factor for systemic HTN, and obstructive apneas may lead to acute BP elevation during sleep,^{12,63} which can result in a loss of the normal nocturnal dipping pattern of BP. A recent meta-analysis found that OSA is associated with a 1.5-fold increase in the prevalence of nondipping BP,⁶⁴ thus suggesting that ambulatory BP monitoring (ABPM) could serve as a surrogate marker for OSA. Support for this possibility comes from reports that nondipping nocturnal BP predicts OSA in subjects undergoing

ABPM.⁶⁵ Furthermore, a recent report from this department indicated a high predictive value for moderate to severe OSA in unselected patients recruited from a HTN clinic who had a nondipping pattern of nocturnal BP on 24-hour ABPM.⁶⁶ These findings support the possibility that ABPM may be a useful biomarker for OSA, irrespective of the clinical index of suspicion for the disorder.

Limitations of ABPM with a pneumatic cuff include the possibility that cuff inflation causes arousal and that the device is unable to track rapid changes in BP associated with individual apneas.^{67,68} Such limitations may be overcome by continuous measurement of BP by finger photoplethysmography, which uses a small cuff fitted to the finger that provides a continuous measurement. This device provides beat-by-beat pressure measurements and gives an indication of BP variability, which is typically increased in OSA.⁶⁹ A novel smart-watch, CareUp (Farasha Labs, Paris, France), has been developed that gives a continuous estimation of BP⁷⁰ and has been validated in a study of 44 subjects.⁶⁷ This simple device may provide an additional method for home BP monitoring, which could be a promising screening method for OSA, although further research of this technique is required before being accepted into clinical practice.

ACTIGRAPHY

Sleep is associated with reduced body motion compared to wakefulness, and lack of body movement is widely used as a surrogate marker for sleep. Actigraphy is the most widely used method, and typically uses an accelerometer that is either a stand-alone device or built into a wristwatch. Actigraphy can be used to estimate daily sleep-wake cycles, which can be clinically useful in the evaluation of many sleep disorders. Actigraphy has been formally evaluated by the American Academy of Sleep Medicine and recognized as a valid research tool in sleep⁷¹ and, more recently, as an alternative to PSG for prolonged monitoring of sleep quality.⁷² Several reviews^{73–75} have indicated that actigraphy can provide clinically useful information about sleep in the natural environment, which may assist in clinical decision-making. However, actigraphy is not reliable in distinguishing different sleep stages and has poor specificity.⁷⁶ In comparison with PSG, actigraphy overestimates total sleep time and underestimates time spent awake.⁷⁷ Actigraphy provides an indirect signal relating to body motion, which implies that estimation of sleep stages is only derived from an assessment of how body motion changes during different sleep stages, and is likely

Fig. 1. Potential physiologic signals for the diagnosis and monitoring of OSA. Signals can be fed wirelessly or via Bluetooth to a router or smartphone and then uploaded to a secured database, whereby end users may access and review the data. BP, blood pressure; ECG, electrocardiogram; EEG, electroencephalogram.

to be of limited accuracy in this determination. However, with improving technology, the role of actigraphy as a screening tool will likely increase and be included in ambulatory diagnostic systems for OSA where accurate measures of sleep staging are not generally required.

Wireless Systems – Biosensors in Obstructive Sleep Apnea

Wireless monitoring systems have been in clinical use for several decades, and an early example involved pressure-sensitive foils placed over the mattress, which provided measures of sleep, heart rate, and respiration.⁷⁸ Wireless devices have greatly improved over subsequent years and benefit from developments in digital technology that are used in signal acquisition and processing.

Radio frequency waves, which are similar to radar technology, can detect small body movements, such as those produced by respiration, which may facilitate the assessment of sleep and wakefulness and of SDB. SleepMinder (ResMed Sensor Technologies, Dublin, Ireland) is a noncontact device that estimates the severity of SDB using a multichannel biomotion sensor and an integrated analysis software program.⁷⁹ The device has been shown to correlate well with PSG in the determination of AHI⁸⁰ and sleep efficiency⁸¹ during controlled laboratory settings. More recently, the device has been reported to be a useful screening tool in the detection of moderate and severe OSA, although having poor accuracy in the setting of mild OSA.⁸²

Actigraphy has been incorporated into many smartphone applications that estimate sleep quality, and additional signals relevant to the assessment of SDB may be obtained from audio and oximetry recordings that have been incorporated

into many wearable recording systems, which may also include monitoring of heart rate.⁸³ Given their wide availability, relatively low cost, and ease of use, smartphones and wearable devices may provide a valuable screening opportunity for the detection of OSA and other sleep disorders,^{84,85} which may also help prioritize patients that require more detailed investigation. Finally, technological advances in telemedicine may strengthen interdepartmental collaboration to improve the overall care of OSA patients.⁸⁶

SUMMARY

Developments in signal technology and analysis provide novel approaches to the assessment of patients suspected of OSA, which range from enhanced analysis of traditional signals to novel signal technologies that provide surrogate markers of OSA. The potential range of novel approaches to the assessment of OSA is illustrated in Fig. 1.

CLINICS CARE POINTS

- When examining the oximetry tracing for features consistent with OSA, ensure that the technology of the recording device has a sufficiently high sampling rate to detect the characteristic fluctuations in oxygen saturation.
- While snoring does not directly relate to OSA, short gaps during prolonged periods of snoring provide an indirect indication of upper airway obstruction.

- The absence of nocturnal dipping of blood pressure is a potential surrogate marker of OSA and is especially important as this represents a cardiovascular comorbidity.

DISCLOSURE

The author has nothing to disclose.

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