CURRENT OPINION

Alternative algorithms and devices in sleep apnoea diagnosis: what we know and what we expect

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Purpose of review
Diagnosis of sleep apnoea was performed in sleep laboratories with polysomnography. This requires a room with supervision and presence of technologists and trained sleep experts. Today, clinical guidelines in most countries recommend home sleep apnoea testing with simple systems using six signals only. If criteria for signal quality, recording conditions, and patient selection are considered, then this is a reliable test with high accuracy.

Recent findings
Recently diagnostic tools for sleep apnoea diagnosis become even more simple: smartwatches and wearables with smart apps claim to diagnose sleep apnoea when these devices are tracking sleep and sleep quality as part of new consumer health checking. Alternative and new devices range from excellent diagnostic tools with high accuracy and full validation studies down to very low-quality tools which only result in random diagnostic reports. Due to the high prevalence of sleep apnoea, even a random diagnosis may match a real disorder sometimes.

Summary
Until now, there are no metrics established how to evaluate these alternative algorithms and simple devices. Proposals for evaluating smartwatches, smartphones, single-use sensors, and new algorithms are presented. New assessments may help to overcome current limitations in sleep apnoea severity metrics.

Video abstract
http://links.lww.com/COPM/A28.

Keywords
oximetry, polygraphy, polysomnography, pulse wave analysis, sleep apnoea, wearables

INTRODUCTION

Sleep apnoea is a global health burden with a high prevalence [1▪▪]. As a consequence of the health burden, diagnostic tools are needed for the diagnosis of sleep apnoea. With the high prevalence there is a high likelihood of having a diagnostic test with a positive outcome whatever test is applied. Even simple tests may result in many positive diagnostic results. Simple tests may be as simple as a few questions. Examples for this are the STOP-BANG, the Berlin Questionnaire and the NO-SAS questionnaire [2]. However, the questionnaires are symptom (sleepiness, snoring) and finding [age, sex, blood pressure (BP), neck circumference] related. Because sleep apnoea occurs during sleep, a state without conscious observation, we assume a recording of physiological signals during sleep provides a more objective assessment. Being a sleep-related breathing disorder, the signals of first choice are respiration based. The signals of second choice are results and consequences of breathing such as changes in oxygen saturation, in heart rate (HR), and in BP. The signals of third choice are surrogates for respiration such as snoring, and movement. A grid for assessing the functions affected by sleep apnoea and the quantitative quality of information derived had been introduced by the SCOPER criteria, assessing Sleep, Cardiovacular, Oxygen saturation, Position, respiratory effort, respiratory flow [3].

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KEY POINTS

- Polysomnography is the reference method for diagnosing sleep apnoea, and remains applicable for clinical research.

- Home sleep apnoea testing is the method accepted in most countries with high-accuracy and established as the work horse for diagnosing sleep apnoea.

- New sensors, wearables, smart algorithms provide a mixture of accuracy and some of them are alternatives worthwhile to be considered as diagnostic tools under the provision that well designed validation studies from multiple sleep centres had been published.

Moreover outcome studies have shown, that counting apnoea and hypopnoea events, and summarizing them to an apnoea–hypopnoea index (AHI) is not enough to predict mortality [4▪▪]. In addition, a few treatment studies have shown, that a simple reduction of the AHI may not improve mortality. Consequently the development of alternative devices and algorithms tries to derive new metrics which might better predict severity of sleep apnoea and may help to phenotype patients to choose a personalized treatment [4▪▪]. Hypoxia and the hypoxic burden are important parameters related to sleep apnoea severity. Derived metrics are the oxygen desaturation index (ODI) and time metrics like time with oxygen saturation below 90% and more similar parameters. Definitely, ODI alone is not an appropriate replacement for AHI. Currently we are thinking to combine different information, such as AHI, ODI, respiratory event duration, sleep fragmentation, symptoms, and cardiovascular/metabolic comorbidity. But this combination is still under discussion and outcome studies are needed for achieving conclusive results. This approach requires further discussion and leads to the idea of 'reinventing polysomnography' and more specifically, the polysomnography (PSG) reporting [5▪]. However, this is a long-term goal because mortality and morbidity data need to be collected.

REFERENCE STANDARD: POLYSOMNOGRAPHY

The reference standard for diagnosing sleep disordered breathing, as defined by the International Classification of Sleep Disorders [6] and as defined by event definitions outlined in the American Academy of Sleep Medicine (AASM) manual for scoring sleep and associated events, is PSG. The signals to be recorded, the technical requirements, the scoring criteria and the reporting of results are all perfectly specified in the AASM manual [7]. PSG requires specially equipped rooms with one bed per room and video recording added, and a continuous supervision by trained persons (sleep technicians) for the night-time recording. After the recording, the data are scored visually by trained sleep scorers (sleep technicians) for sleep stages, apnoea, hypopnoea events, arousal, movement, and further events [7]. A report is generated. The report includes the number of apnoea and hypopnoea events and relates them to the total sleep time (TST). Once related to TST, this is called AHI with events per hour of sleep. This index serves as a severity measure for sleep apnoea. An AHI below 5/h is rated as normal, AHI between 5 and 15 is rated as low apnoea severity, AHI between 15 and 30 as moderate apnoea severity and AHI above 30 as severe sleep apnoea. Moderate and severe sleep apnoea require treatment to reduce the risk for subsequent cardiovascular mortality. The resulting report is interpreted by experts, which altogether is a costly and time consuming investigation. This high standard for diagnosis will remain to be a clinical research tool and a reference when testing new algorithms and devices against the gold standard [8].

HOME SLEEP APNOEA TESTING

Following the high prevalence, for clinical purposes, recording devices for sleep disordered breathing were reduced to the essentials [9,10▪]. The agreed essentials are airflow, respiratory effort, oxygen saturation, HR (or ECG or pulse rate), body position, some surrogate for sleep time (could be just self reported), sometimes snoring [10▪]. Devices based on these six channels/ signals had been validated against the gold standard PSG and have proven to deliver accurate diagnoses when compared between centres [11]. Criteria for their accuracy had been documented and are considered for out-of-centre type of recording sleep apnoea [3]. Devices are approved to be good enough to distinguish obstructive, mixed, central apnoea events, and hypopnoea events. Recommendations and guidelines had been published for general medical care [2]. Limitations for applying home sleep apnoea testing devices (also called polygraphy) had been specified and noted. These are comorbidities like cardiovascular disorders, neurological disorders, other sleep disorders, and more complex sleep disordered breathing such as nocturnal hypoventilation, which require CO_2 recording [12].

MOVEMENT RECORDING

To recognize sleep stages and more specifically sleep apnoea body movements during sleep had been recorded for many years. In the very beginning of sleep research, more than 100 years ago, it was

observed that the amount and extend of movement is closely related to the deepness of sleep. Deep sleep, which we now call slow-wave sleep, according to electroencephalography findings, is associated with very little movement. Dream sleep, rapid eye moement (REM) sleep, is associated with atonia interrupted by very short twitches. And light sleep, sleep stages N1 and N2, are associated with just a little movement. Sleep apnoea interferes with this movement pattern dramatically. Apnoea events with increasing respiratory effort towards the end of each apnoea event and then arousals just at the end of each apnoea events often are reflected by distinct, periodic, and characteristic movement patterns. This can be picked up by any movement detector and recognized by smart software, focussing exactly on this distinct pattern [13]. First sensor approaches which used this kind of movement recording, to characterize sleep and detect sleep apnoea, were ballistocardiographic sensors. These evolved into 'static charge sensors' and into Emfit foils placed in the bed of a sleeping person [14]. The huge advantage of movement sensors in a bed underneath a sleeping person is, that a good sensor can record coarse body movements, respiratory related movements, and, if sensitive enough, cardiac movements as well. This is the reason for the term 'ballistocardiogram'. The combination of the three signals can be exploited to a large extent for providing a relatively good assessment on sleep stages and sleep disordered breathing, although obviously limitations are inherent to this methodology.

These movement sensors to detect apnoea events where specifically attractive for detecting apnoea events in newborns because being contact-free. Lately the foils shrinked to a movement sensitive band, and are commercialized together with smartphone apps responsible for the signal analysis (e.g., Beddit by Apple). This system had been validated in a sleep centre for the detection of sleep apnoea by combining the information gained from body movements, respiratory movements and HR using smart algorithms [15]. However, this potentially high accuracy is no longer mentioned, when the system is marketed as a gadget for quantifying sleep quality.

Activity monitoring can be done nonobtrusive and with low costs using radar technology [16]. Since a couple of years, several engineering companies have developed radar technology devices which are placed on a bedside table and record the movements of the sleeping person [17]. These devices essentially derive the same signals as ballistocardiography: coarse body movements, respiration related movements, and the HR. Consequently, algorithms and accuracy are similar to that technology.

A simple way to record movements for a long time in sleep medicine is actigraphy. Actigraphy with a wrist worn watch had been used in sleep apnoea to objectify sleep duration to optimize 'total sleep time' estimation which is needed for the calculation of the AHI. Wrist worn actigraphy may be used with traditional devices as recommended for sleep apnoea by clinical practice guidelines [18]. This is best validated. An estimation of TST may be performed by ballistocardiography, Emfit sensors and other sensors placed in the bed. Validation studies show varying results, depending much on the patient group and algorithms used. An estimation of TST may be performed by noncontact radar devices placed next to the bed. Validation studies for TST are scares, especially for patients. An estimation of TST may be performed by evaluating HR or pulse rate as well. For this kind of indirect estimation of TST, no systematic validation studies are available. Beyond this, no new studies on actigraphy in sleep apnoea were published.

OXIMETRY RECORDING

Apnoea events with a cessation of breathing cause oxygen desaturation. The severity of oxygen desaturation depends on the duration of the event and the baseline value of oxygen saturation. The exact drop of oxygen saturation is determined by the oxygen binding curve and the placement of the sensor. According to the oxygen binding curve, pH, temperature, and other physiological conditions mediate the drop in oxygen saturation. The placement of the sensors is of specific importance, because usually the sensor is placed on the finger which is far in the periphery (Fig. 1). A vasoconstriction during an apnoea event will reduce blood flow to the periphery and will show artificially low oxygen saturation values when compared with other sensor positions. Independent of this complex nature of the signal, the signal itself is very intuitive and therefore much liked as a measure for sleep apnoea [19]. According to the AASM manual [7] the drop of oxygen saturation is a diagnostic criterion for defining hypopnoea events. As it is understood today, counting apnoea and hypopnoea events (i.e., AHI) is not a sufficient measure to determine severity of sleep apnoea, oxygen saturation is a good candidate, because hypoxia is known as a parameter damaging physiological functions and cognition. A recent study introduced a new metric called oxygen desaturation rate and related this parameter to arterial hypertension in patients with sleep apnoea [20].

Smartwatches with LED technology on the bottom of the watch can record oxygen saturation just
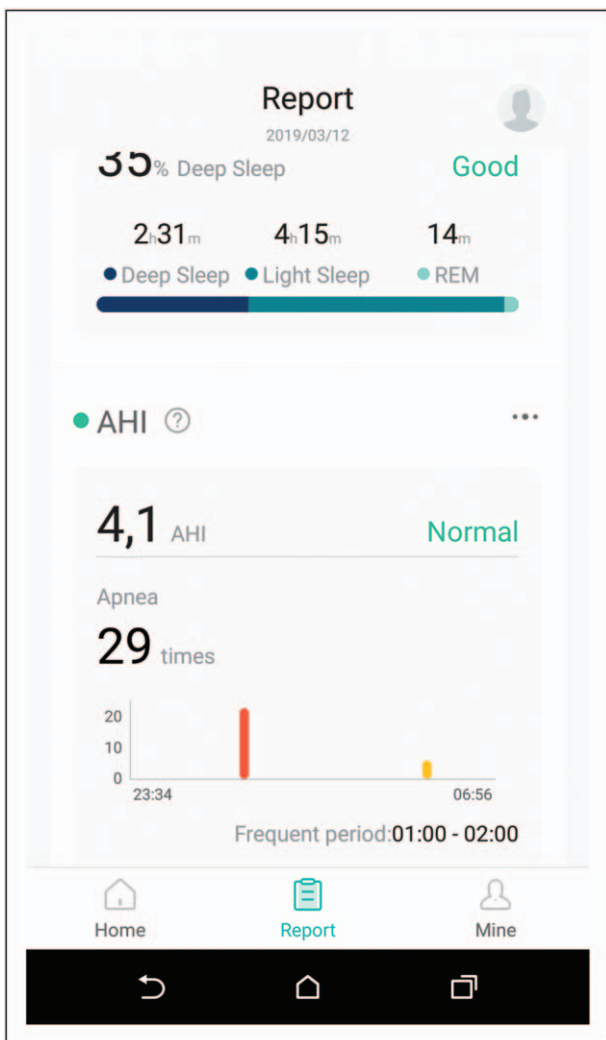
FIGURE 1. Smart ring produced sleep apnoea report. (a) Shows the screen of the smartphone app after downloading data from the wearable finger ring (Sleepon device). The screen shows one night of oxygen saturation trace, pulse rate, estimated sleep stages, and motion events. With a cursor, it is possible to go to selected positions of the recording and display details in a textual box. (b) Shows a brief report with a calculated apnoea hypopnea index, here 4.1 events/h. This is scored as normal. My own original data at our sleep centre (Thomas Penzel).

on the fly, if a good signal processing of the pulse waves is implemented. The smartwatch and all three finger rings depicted in Fig. 2 allow recording of photoplethysmography. Most of them present oximetry signals to the user. With reasonably good signal accuracy oxygen desaturations can be counted and an ODI, a surrogate for an AHI can be derived [21]. When getting an ODI, the physiological modifiers mentioned above should be recalled before using this value for a diagnostic decision.

FIGURE 2. A demonstration of a variety of wearables on one hand. The hand demonstrates, from thumb onwards has the Circul, Sleepon, and Oura ring attached, a Smartwatch with PPG, Photoplethysmography recording and a sleep analyser app, and the M1 Sleepimage device next to the hand to be attached on the chest. My own camera with my own hand (Thomas Penzel).

ECG RECORDING

With each apnoea event sympathetic and parasympathetic tone changes cyclic. This is related to the physiologic diving reflex and the hypoxia event during each apnoea [22]. During sleep, sympathetic tone is low and parasympathetic tone is elevated. This results in a low HR during sleep. When an apnoea event begins, this condition of sympathetic and parasympathetic tone is the starting point. During the apnoea event, along with the oxygen decrease sympathetic tone increases, but this cannot be translated into an increase in HR, because no breathing is possible. When the apnoea event is terminated, an overshoot of sympathetic activity with a sudden increase in HR occurs, which lasts for a couple of seconds and then HR decreases again. This pattern had been described as cyclical variation of HR. It is so characteristic, that it had been proposed to be used as a diagnostic tool for the detection of sleep apnoea [23,24]. This method had been implemented in long-term ECG recording software and gives an indication for further investigations for sleep disordered breathing. The method had been implemented in multiple wearable devices using pulse rate instead of HR (compare Fig. 2) and smart algorithms to increase the probability for an accurate detection of apnoea events together with other recorded information [25].

PULSE WAVE RECORDING

Pulse oximetry sensors provide a photoplethysmographic signal in addition to the calculated oxygen

saturation value. This signal follows the pulse wave wherever recorded. The finger pulse wave appears to be similar to BP because it reflects the BP wave travelling into the periphery. However, the pulse wave amplitude is modulated by local effects vascular properties, like arterial blood vessel stiffness, vasocontriction of vessels, and local microcirculatory effects. Vasoconstriction reflects sympathetic and parasympathetic activity. As both are heavily modulated by sleep apnoea, pulse wave amplitude follows closely apnoea and hypopnoea events. This covarying relationship is similar to the covarying of HR with apnoea and hypopnoea events. As such it is possible to detect sleep apnoea from pulse wave amplitude modulations [26]. Moreover, it is possible to derive sleep stages from the pulse wave amplitude modulations. It is particularly striking that REM sleep is well reflected by pulse amplitude modulations [27]. All this together allows to diagnose sleep apnoea from the pulse wave and recently it was possible to distinguish central and obstructive sleep apnoea events from details of the pulse wave curve during the respiratory events [28].

SNORING RECORDING

It is usually reported that snoring accompanies obstructive sleep apnoea. In fact, this is one of the leading complaints when subjects seek for help at a sleep centre. However, regular snoring is annoying but not characteristic for sleep apnoea. It may reflect vibrations of upper airway tissue and not necessarily an upper airway obstruction. If an upper airway obstruction occurs, snoring becomes irregular and the sound changes. An analysis of the snoring sound details can therefore support the diagnosis of sleep apnoea. In this case a microphone is place over the trachea and the recorded signal is called tracheal sound. Sophisticated analysis of tracheal sound allows to extract respiratory flow information with a detection of inspiration and expiration, upper airway obstruction with a characterization of obstructive and central apnoea events, and, if combined with a pressure sensor, then even an estimation of respiratory effort [29]. This kind of sensors had been integrated in a French system used for PSG and for polygraphy for the diagnosis of sleep disordered breathing [30].

FUTURE PERSPECTIVES

Many of the sensor technologies, like movement sensors with radar technology, oximetry sensing at the wrist, HR detection, pulse wave recording, and sound/snoring recording have the potential to become wearable and to be integrated into

smartwatches, fitness trackers, Bluetooth connected sensors, and even integrated into smartphones [31,32]. Smartphones do provide the data storage capacity for large amount of recorded data, and the computational power to analyse complex signals. They also provide the communication power to transmit recorded or compressed data to a medical cloud where additional big data analysis is performed. Even more sophisticated algorithms in the medical data cloud can provide a comparison with thousands of other recordings and based on this, provide an adequate evaluation and recommendation feedback to the user or patient. This means that medical diagnostics for sleep apnoea can become much easier accessible when using the new technologies (Fig. 1).

Devices come from consumer devices designed to quantify yourself and aiming for improving performance and physical fitness and now they evolve to medical devices providing some kind of diagnosis with until now, uncertified accuracy. This means that validation studies are needed, that data transmission and data storage needs to be secure and data access must be regulated [33,34]. The European funded ASCLEPIOS project is developing secure access for a medical cloud for sleep medicine data (https://www.asclepios-project.eu/ accessed 16 July 2020).

Certainly in future both, consumer devices and medical devices will find their market place. Perhaps a distinction between the two worlds of devices is the validity of the result. Currently validity can be evaluated on an event by event basis (has an apnoea event be correctly identified and classified). This is important for a physician to decide on possible therapy. And validity can be evaluated on an overall decision with sleep apnoea being present or not, like a traffic light with red, yellow, green validated against AHI thresholds (5, 15, 30 events/h). This kind of validity may be enough for consumer devices. Currently both kinds of validity testing are applied to both kind of devices with a high variability in accuracy.

The new thread of pandemic diseases, when hospital-based sleep centres are forced to close, will strengthen the use of home-based diagnosis using new digital technologies. It will certainly strengthen the application of noncontact recording devices, as mentioned here. However, validation studies with a broad range of patients need to precede the clinical use of these devices.

CONCLUSION

The traditional diagnostic tool for sleep apnoea is PSG. However, this is no longer the tool for clinical practice. The high prevalence and the global burden of sleep apnoea require easy accessible devices and

alternative tools with high accuracy and reliability, adequated certifications and well known and documented limitations for their application. Polygraphy is the currently used tool. Simpler tools, such as smartphone supported tools are about to come, but have not been validated enough.

A clinician might want to know which of the new tools and methods could be used for which patient. To answer this question, studies are needed which check the precision in distinguishing between normal, mild, moderate sleep apnoea in unselected patient groups. However, this kind of studies are not available for the new tools. Tools, if validated were usually tested in extreme patients. Therefore, a clinicians guide to check devices is still the grading of methods according to the SCOPER criteria [3].

In addition to the challenge of high prevalence, sleep medicine faces the challenge of identifying the right patients which have an increased mortality risk and profit most from treatment. The traditional severity parameter AHI has limitations for this assessment. New devices and algorithms provide the potential to give better severity metrics. But his requires long-term mortality and treatment outcome studies and cannot be concluded with short-term studies.

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Conflicts of interest

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