




BMJ Open Protocol of the SOMNIA project: an observational study to create a neurophysiological database for advanced clinical sleep monitoring

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ABSTRACT

Introduction Polysomnography (PSG) is the primary tool for sleep monitoring and the diagnosis of sleep disorders. Recent advances in signal analysis make it possible to reveal more information from this rich data source. Furthermore, many innovative sleep monitoring techniques are being developed that are less obtrusive, easier to use over long time periods and in the home situation. Here, we describe the methods of the Sleep and Obstructive Sleep Apnoea Monitoring with Non-Invasive Applications (SOMNIA) project, yielding a database combining clinical PSG with advanced unobtrusive sleep monitoring modalities in a large cohort of patients with various sleep disorders. The SOMNIA database will facilitate the validation and assessment of the diagnostic value of the new techniques, as well as the development of additional indices and biomarkers derived from new and/or traditional sleep monitoring methods.

Methods and analysis We aim to include at least 2100 subjects (both adults and children) with a variety of sleep disorders who undergo a PSG as part of standard clinical care in a dedicated sleep centre. Full-video PSG will be performed according to the standards of the American Academy of Sleep Medicine. Each recording will be supplemented with one or more new monitoring systems, including wrist-worn photoplethysmography and actigraphy, pressure sensing mattresses, multimicrophone recording of respiratory sounds including snoring, suprasternal pressure monitoring and multielectrode electromyography of the diaphragm.

Ethics and dissemination The study was reviewed by the medical ethical committee of the Maxima Medical Center (Eindhoven, the Netherlands, File no: N16.074). All subjects provide informed consent before participation. The SOMNIA database is built to facilitate future research in sleep medicine. Data from the completed SOMNIA database will be made available for collaboration with researchers outside the institute.

Strengths and limitations of this study

- The Sleep and Obstructive Sleep Apnoea Monitoring with Non-Invasive Applications database will contain the gold standard in clinical sleep monitoring combined with several new techniques to monitor sleep and sleep-related phenomena.
- We create a large dataset including both adults and children, covering the whole spectrum of sleep disorders.
- The focus of this database is on diverse (sleep) pathologies and comorbidities, derived from a 'real-world' clinical setting.
- The size and variety of the dataset will make it a valuable source for a broad range of studies on sleep monitoring and diagnostics.
- The data will be available for collaboration on research in sleep medicine.

INTRODUCTION

Although we spend about one-third of our lives sleeping, sleep is still one of the most mysterious human behaviours. Because of the unconscious nature of sleep, studying this behaviour depends heavily on technology. Since the discovery of the human electroencephalography (EEG) in 1929,¹ this technique has been used to characterise the sleeping brain. In the mid-1930s, different sleep stages were first described² and only in 1953 rapid eye movement (REM) sleep was formally described.³ In modern sleep medicine, EEG is still the most important component of polysomnography (PSG).⁴ With PSG, data about sleep stages and various physiological measures, such as respiration, heart rate, leg movements and body position are acquired and analysed simultaneously to

gain insight into sleep patterns and the presence of sleep disorders.

With the large number of PSG sensors, sleep registrations contain a wealth of information. However, currently, this source is not used to its full potential. Although automatic analyses are available, in clinical practice PSG is still typically scored manually by a skilled technician.⁵ With the recent advances in signal analyses and machine learning, we are now capable of capturing even more complex information/patterns from the PSG.⁶ New parameters for diagnosis, symptom severity or clinical outcome might be found this way. Moreover, automatic detection of pathological phenomena is improving, such as sleep-related breathing events,^{7,8} movements related to movement disorders⁹ or nocturnal behaviour indicative of parasomnia¹⁰ is improving. Both traditional PSG sensors and new devices can be used for this purpose. Large, well-characterised datasets containing divergent sleep pathologies are now needed to develop and validate these kinds of algorithms.¹¹

Because of the complex setup, PSG has limitations. Subjects have to sleep with many sensors attached to their head and body, often in an unfamiliar hospital environment. This may cause stress or anxiety and influence the findings (first night effect).¹² Many sleep disorders show night-to-night variation, so clinical events can easily be missed with only one night of observation. These drawbacks are even more pronounced for the registration of sleep and sleep disorders in special populations, such as children, elderly and intellectually disabled subjects. These patients are easily intimidated by the large number of sensors and due to sensitive skin the use of contact sensors can be problematic. Furthermore, (visual) sleep scoring in these groups is more difficult and requires specific training.¹³

PSG remains the gold standard in sleep monitoring and diagnosis of sleep disorders, but many alternative techniques are being developed. These include a wide range of sensing modalities including wearable sensors and sensor mattresses.¹⁴ These advanced techniques have in common that they are non-invasive and minimally obtrusive, and therefore better accepted by patients. Furthermore, they are easy to use over longer periods of time and applicable in the home situation. Possibly these innovative solutions can play a role in treatment monitoring and the diagnosis of sleep disorders or eventually even substitute PSG in selected cases.

Application of sleep monitoring devices can roughly be divided into two categories: sleep staging and clinical event detection. Sleep stages are by definition based on EEG characteristics.⁴ However, surrogate measures based on movement or cardiorespiratory parameters are explored as well. Actigraphy is already a widely used measure for sleep/wake classification.¹⁵ The main application is to gain insight in rest-activity patterns over longer periods of time, for example, in case of (suspected) circadian rhythm disorders.⁴ Actigraphy has reasonable validity and reliability in healthy individuals with relatively good sleep

patterns. However, the validity in special populations or in individuals with poor sleep or other sleep-related disorders is more questionable.¹⁶

Recently, sleep staging algorithms based on cardiac and respiratory signals have shown promising results in healthy subjects.¹⁷ They are based on sleep-stage specific patterns in heart rate variability (HRV) and respiration.¹⁸ These features can be derived from the ECG and respiration belts, but also from photoplethysmography (PPG) signals, which can be incorporated in wearable devices.¹⁹ Validation for this type of algorithms in patients is limited and has proven to be more challenging.^{20–22}

Here, we describe the aims and methods of the Sleep and Obstructive Sleep Apnoea (OSA) Monitoring with Non-Invasive Applications (SOMNIA) project, which will yield a database containing clinical PSG combined with different advanced non-invasive sleep monitoring techniques in a large cohort of both adults and children with various sleep disorders from a tertiary referral sleep centre. Gold standard PSG will be augmented with a number of promising non-invasive monitoring systems, including wrist-worn PPG and actigraphy, pressure sensing mattresses, high fidelity acoustic recordings, suprasternal pressure monitoring and multielectrode electromyography of the diaphragm. The additional technologies are chosen based on their unobtrusiveness, broad range of sensing approaches, potential clinical value and previous proof of concept and validation studies.^{19,23,24}

An important focus of the SOMNIA database is on monitoring techniques for OSA, because this disorder is highly prevalent²⁵ and has serious (potential) health consequences.^{26,27} Furthermore, in the current PSG montage, monitoring respiration requires the most obtrusive sensors.⁴ However, the database will also include insomnia, central disorders of hypersomnolence, circadian rhythm sleep-wake disorders, parasomnias, sleep-related movement disorders and cover as such the complete spectrum of sleep disorders, including complex and combined pathology.

The SOMNIA dataset can be used in several ways. First, it will allow validation of new sleep monitoring techniques in a representative group of sleep clinic patients. Second, the diagnostic value of these different techniques can be assessed, as well as additional indices that can be derived by combining different new and/or traditional PSG techniques. Finally, the data can be used to study the physiology of sleep (disorders) in a cohort of patients including complex pathology and comorbidities. The SOMNIA database will be made available as a 'neurophysiological biobank', to enable multidisciplinary collaborations to improve sleep diagnostics.

METHODS AND ANALYSIS

Population

The SOMNIA database will be created within Sleep Medicine Center Kempenhaeghe (Heeze, the Netherlands), a third-line expert centre for multidisciplinary sleep

medicine. Subjects are recruited among patients who are planned for a PSG as part of the standard diagnostic process. We aim to include 2000 adults and 100 children with a variety of sleep disorders. We will include a minimum of 100 adults and 10 children per International Classification of Sleep Disorders (ICSD) diagnostic category: insomnia, sleep-related breathing disorders, central disorders of hypersomnolence, parasomnias and sleep-related movement disorders. For the diagnosis of ICSD category circadian rhythm sleep-wake disorders, usually no clinical PSG is made, so we do not expect to include these patients as a separate group.

No formal exclusion criteria apply for this study. The overall goal of the study is to collect data of a representative sample of a patient population in a dedicated sleep centre, so the dataset will include patients from the complete spectrum of (complex) sleep disorders. However, patients with very complex sleep pathology or particularly severe comorbidity will most likely not be included, because these patients have higher clinical demands and data may be too difficult to interpret and less useful in groupwise comparison studies. The decision whether or not to ask a patient for inclusion in the study will be made by the treating physician.

Typical numbers of clinical PSGs made per ICSD disorder category, per year for the recruiting centre are: 400 insomnia, 850 sleep-related breathing disorders, 60 central disorders of hypersomnolence, 100 parasomnias and 200 sleep-related movement disorders. With a practical estimate of 1:3 patients eligible for the study and willing to participate, we are planning 4 years for the study to run.

Recruitment and general study procedure

Eligible patients who are scheduled for a PSG as part of usual medical care receive information about the study aims, procedures and the various additional sleep monitoring techniques. Depending on the technical utilities in the individually designated PSG bedroom, experimental sleep monitoring systems are added to the standard PSG. When it is not possible to add all sensors, a relevant subset is chosen. Participation in the study may never lead to interference with the clinical PSG. Depending on the clinical question underlying the sleep assessment, patients will use their regular medication and/or Continuous Positive Airway Pressure (CPAP) device during the sleep recording. All medication and other therapies are registered in the database.

Polysomnography

PSG registrations are made for one night. Patients stay at the inpatient clinic in an individual, sound-proof bedroom, under supervision of a sleep technologist.

Sleep is polysomnographically monitored using a dedicated recording system (Grael PSG, Compumedics, USA). For technical details, see [table 1](#). The primary sleep registration is based on the guidelines of the American Academy of Sleep Medicine (AASM),⁴ and consists of 6-channel EEG, 2-channel electro-oculography and electromyography of

the mentalis muscle. Polygraphy recordings include ECG, respiratory flow (nasal and oral thermistors), nasal pressure (nasal cannula), respiratory effort based on thoracoabdominal respiratory inductance plethysmography, oxygen saturation (transmissive finger PPG), snoring (piezoelectric tracheal microphone), body position (gravity-based electric sensor) and electromyogram (EMG) of tibialis anterior muscle. A time-synchronised video registration (infrared camera) is part of the standard recording. In selected cases based on a specific clinical question, additional measurements may be added; these include, for example: oesophageal pressure monitoring (eg, for suspected OSA while standard PSG was negative, or a clinical suspicion of both central and obstructive events), transcutaneous CO₂ measurements (eg, for a clinical suspicion of nocturnal hypoventilation) and additional EMG montages (eg, for suspected REM sleep behaviour disorder, propriospinal myoclonus or bruxism).

Sleep and event scoring

Sleep and associated events are scored according to the AASM 2015 criteria⁵ using ProFusion software (ProFusion PSG V.4.00 (build 423), Compumedics, Australia). Respiratory events, snoring and limb movements are automatically scored by the software and subsequently checked and corrected by a certified sleep technician. All other events (eg, behaviour related to parasomnias or epilepsy, etc.) and sleep stages are scored by the technician without automatic prescoring. When oesophageal pressure (PES) monitoring is used, PES events are scored manually. Full scoring of Respiratory Event Related Arousals is available when performed for diagnostic purposes on clinical grounds.

Clinical data

At intake, the clinician records primary clinical data including demographic information, current medication, comorbidities and the results of screening questionnaires (if applicable; Epworth Sleepiness Scale,²⁸ Pittsburgh Sleep Quality Index,²⁹ Insomnia Severity Index,³⁰ Hospital Anxiety and Depression Scale,³¹ Checklist Individual Strength fatigue,³² Paris Arousal Disorders Severity Scale (PADDS)³³). A final primary diagnosis is entered after the diagnostic trajectory for sleep pathology is finished. The diagnoses are coded according to the ICSD-2 criteria³⁴ which can be recoded according to ICSD-3 criteria⁴ but contain some more subcategories especially in the insomnia category. Secondary sleep pathology and categories of comorbidities are also recorded.

Experimental measurement modalities

Wrist-worn PPG and actigraphy

This wrist-worn sensor is a CE-marked logging device combining reflective PPG and a three-axial accelerometer sensors (Philips Research, Eindhoven, the Netherlands). For technical details, see [table 2](#). The logging device is mounted on the non-dominant wrist of the participant (same hand as the finger PPG sensor), with the sensor



Table 1 Technical specifications of the polysomnography (PSG) sensors

PSG measure	Sensor	Manufacturer	Placement	Sampling frequency (Hz)	High-pass filter (Hz)	Low-pass filter (Hz)
EEG	Ag/AgCl surface electrode	MFI B.V., the Netherlands	F4-M1, C4-M1, O2-M1, F3-M2, C3-M2, O1-M2 (according to international 10–20 system)	256	0.3	70
EOG	Ag/AgCl surface electrode	MFI B.V., the Netherlands	E1-M2 (E1: 1 cm below and 1 cm lateral to the left outer canthus), E2-M2 (E2: 1 cm above and 1 cm lateral to the right outer canthus)	256	0.3	70
EMG chin	Ag/AgCl surface electrode	MFI B.V., the Netherlands	Chin 1: 2 cm below inferior edge of the mandible and 2 cm to the left of the midline Chin 2: 2 cm below inferior edge of the mandible and 2 cm to the right of the midline Chin 3: On the midline 1 cm above inferior edge of the mandible	512	15	150
ECG	Electrode H34SG, ECG +EEGEL 46 mm	Kendall, Ireland	Single modified electrocardiograph Lead II torso electrode placement	512	0.3	70
EMG tibialis	Electrode H34SG, ECG +EEGEL 46 mm	Kendall, Ireland	Longitudinally on both legs and symmetrically in the middle of the anterior tibialis muscle 2–3 cm apart	512	10	100
Airflow:						
Oronasal thermal airflow	SKU thermocouple airflow sensor	Compumedics, Australia	Infranasal	128	0.1	15
Nasal pressure transducer	Cannula 4000F, tube length 7 in	Salterlabs, USA	Infranasal	128	0.1	15
Respiratory effort:						
Respiratory inductive plethysmography (RIP)	Dual thoracic abdominal RIP bands	Compumedics, Australia	Mid thorax and mid abdomen	128	0.1	15
Oesophageal manometry	Gaeltec CTO-1 single sensor catheter	Gaeltec, Ireland	Intraoesophageal, tip of pressure sensor above the diaphragm	128	DC	15
Oxygen saturation:						
Transmissive PPG/pulse oximetry	NONIN Purelight, flex sensor 8000J	Compumedics, Australia	Ring finger of the non-dominant hand	16	–	–
Snoring:						
Condensor mic. sensor	Grael Tracheal Microphone	Compumedics, Australia	2 cm lateral to the cricothyroid cartilage	1024	10	100
Body position:						
Gravity-detecting electric sensor	Grael position sensor	Sleepsense, USA	Placed on the front of the thoracic RIP belt	16	–	–

Continued

Table 1 Continued

PSG measure	Sensor	Manufacturer	Placement	Sampling frequency (Hz)	High-pass filter (Hz)	Low-pass filter (Hz)
Transcutaneous CO₂	SDMS	Sentec, Swiss	Earlobe (or forehead in children)	32	–	–
Infrared video:						
Camera	DinionHD 1080p IP-camera	Bosch, Germany	At the ceiling above the bed	–	–	–
Infrared light source	Raymax50	Raytec, UK	At the ceiling above the bed	–	–	–

EEG, electroencephalography; EMG, electromyogram; EOG, electro-oculogram; PPG, photoplethysmography; SDSM, SenTec Digital Monitoring System.

facing the skin on the dorsal side of the hand, above the ulnar styloid process (see figure 1).

The PPG logging device used in this project has been engineered to permit accurate PPG measurements, including the possibility to access data on beat-to-beat variability. Such measurements can be used to analyse HRV during the night, or to assess different cardiorespiratory parameters related to sleep.¹⁹ PPG algorithms have been developed to extract cardiac parameters such as average heart rate, HRV, as well as respiratory variables.^{19 35 36}

The clocks of the PPG sensor and the PSG are synchronised by compensating the clock offset and drift, based on an interpolated (at 4 Hz) time series comprising the interbeat intervals detected from the PPG and another series from the interbeat intervals calculated from R-peaks detected from the ECG signal from the PSG. This guarantees that the recordings are perfectly aligned to the start time and that there is no clock drift between the two recorders.¹⁹

Table 2 Technical specifications of the experimental monitoring devices

Device	Manufacturer	Placement	Sampling frequency	Synchronisation to PSG
Wrist-worn reflective PPG and actigraphy	Philips Research, the Netherlands	Non-dominant wrist, dorsal side of the hand, above the ulnar styloid process	PPG: 32 Hz Accelerometer: 128 Hz	Cross correlation with PSG recorded ECG/PPG interbeat intervals
Bed pressure sensor	2M Engineering, the Netherlands	Under the mattress: shoulder region, abdominal region, hip region (figure 1)	100 Hz	Sync pulse every 10 min (via X-Link)
Acoustic signal registration:				
M23 microphone (high end)	Earthworks, USA	Top end of the bed, midline (figure 2)	48 kHz	Continuous sync signal (via X-Link)
ECM8000 microphone	Behringer, Germany	Top end of the bed, sides (figure 2)	48 kHz	Continuous sync signal (via X-Link)
Diaphragm electromyography	Electrode H34SG, ECG +EEG EL 46mm, Kendall, Ireland	In line in the sixth and seventh intercostal spaces; six on the frontal and two on the dorsal diaphragm. Reference on the sternum (figure 1)	512 Hz	not applicable (recorded with PSG recorder)
Suprasternal pressure monitoring				
Pressure sensor	Sensym, SDX010IND4	Over the trachea in the sternal notch (figure 1)	128 Hz	NA (recorded with PSG recorder)
Tracheostomy fixation	Provox Optiderm Round 7255			
Adapter	3D printed custom device			

EEG, electroencephalography; PPG, photoplethysmography; PSG, polysomnography.

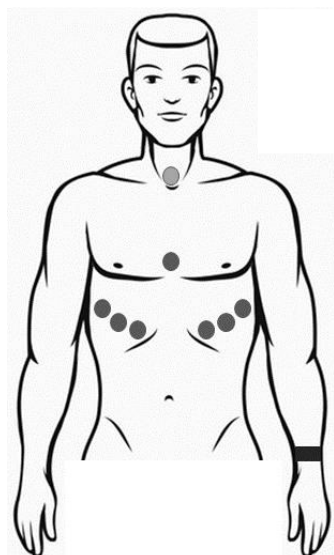


Figure 1 Placement of the body-worn experimental sensors. Light grey circle: suprasternal pressure monitoring; Dark grey circle: diaphragm EMG; Dark square: wrist-worn photoplethysmography. EMG, electromyogram.

Bed pressure sensor

The bed sensor system (2M Engineering, the Netherlands) is a set of highly sensitive, optical pressure sensors located between the bed base and the mattress. Three independent, contact-free sensors record pressure changes to a local storage device with a sample frequency of approximately 100 Hz (see [table 2](#)). Each sensor registers global pressure changes in one zone of the bed. They are located under the shoulder region, under the abdominal region and under the hip region. Large body movements like bed occupancy and turning will be extracted from the recorded pressure signal.²⁴ Besides large pressure changes, the recorded signals also contain ballistic information about vital signs like breathing rate and heart rate.^{37 38}

To postsynchronise the recorded data with the PSG data, a sync-pulse is stored locally but also sent from the bed sensor system to the PSG recording system every 10 min. The sync-pulse is recorded by the PSG system using an additional device for external signals (X-link, Compumedics USA), and synchronised with the PSG signals by the PSG software. Time synchronisation with the bed sensor is achieved by cross correlating these sync pulse signals.

Audio recording for snoring analysis

Nocturnal sounds are recorded using five non-contact omnidirectional condenser measurement microphones (see [table 2](#)); two for high-quality recordings (Earthworks M23) and three for average quality recordings (Behringer ECM8000). The microphones are placed at different heights at the top end of the bed, 60–120 cm from the head (see [figure 2](#)). Signals are recorded by a digital field recorder (Zoom F8) with a sampling frequency of 48 kHz and a bit depth of 24.

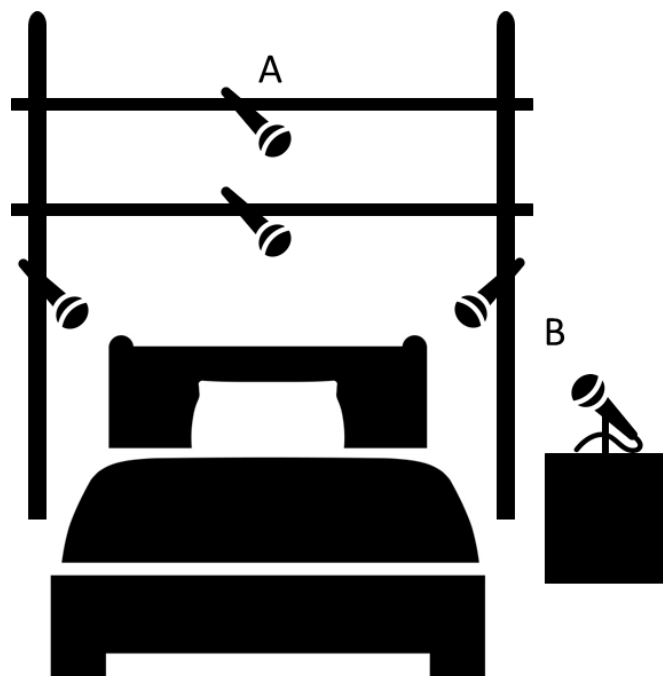


Figure 2 Microphone set-up at the top end of the bed. (A) Two microphones for high fidelity recordings (Earthworks M23) are placed at different heights at the midline of the bed. (B) Two microphones for average quality recordings (Behringer ECM8000) are placed at the same height at the sides of the bed and one on the night stand.

To synchronise the sound and PSG recordings, a modulated sinewave to yield a binary ‘code’ with a known time relation is generated using a USB development tool (C5505 eZdsp, Texas Instruments) and simultaneously fed to the audio recorder and PSG system using an additional device for external signals (X-link, Compumedics USA). The modulated sinewave is recorded synchronously with the PSG signals by the PSG software. These recordings are cross correlated for time synchronisation.

Diaphragm electromyography

Monitoring the electric activity of the diaphragmatic and intercostal muscular system is the most direct way to obtain information on respiratory muscle function.³⁹ Eight unipolar surface electrodes are symmetrically placed in line in the sixth and seventh intercostal spaces; six on the frontal and two on the dorsal diaphragm.⁴⁰ The reference electrode is placed on the sternum (see [figure 1](#)). The extra EMG signals are recorded using direct input channels of the PSG recorder (see [table 2](#)).

Suprasternal pressure monitoring

For suprasternal pressure monitoring, a microphone is embedded in a cuff and placed over the trachea in the sternal notch.⁴¹ This device is used as a pressure transducer. Provided that the cuff is adequately sealed to the skin to ensure an airtight cavity, changes in intrathoracic pressure can be converted into a legible signal of respiratory effort.²³

Here, we use an in-house manufactured adaptation of the suprasternal pressure sensor based on a commercially available pressure sensor (Sensym, type: SDX010IND4), which is placed over the suprasternal notch and attached to the skin using a tracheostomy fixation adhesive (Provox Optiderm Round 7255). A custom-made 3D-printed adapter enables the pneumatic coupling to the pressure sensor. The signal is filtered and split into a respiratory signal and audio envelope. For respiration, the signal is limited by a low-pass 15 Hz filter while for removing cardiac artefacts an extra notch filter at 1.6 Hz is applied. For snoring, the signal is bandpass filtered between 30 and 450 Hz and rectified after which the envelope is determined and the signal is dB scaled. The suprasternal pressure signals are recorded using direct input channels of the PSG recorder at a sampling rate of 128 Hz (bandpass filter DC–35 Hz). In addition, the original unfiltered suprasternal pressure signal is also recorded as an extra channel (sampling rate 1024 Hz, bandpass filter DC–285 Hz).

Database

When the diagnostic trajectory is finished and the patient has received a final diagnosis based on the PSG, all clinical and experimental data are combined. All data are converted to BioSemi Data Format,⁴² a 24-bit version of the 16-bit European Data Format 'plus' (EDF+). Sensor data are synchronised to the PSG and the data are transferred to the research database. Datasets that are exported for scientific research are pseudonymised using a study specific, unique coding, so different SOMNIA datasets cannot be related without the key file which is kept at Kempenhaeghe.

DISCUSSION

SOMNIA opportunities

Here, we describe the aims and methods of the SOMNIA project, to create a large-scale database containing standardised PSG data and data from new, unobtrusive technologies to measure sleep (related) phenomena, in a real-world clinical setting. The current framework facilitates the validation of such new techniques and allows the diagnostic value of these techniques to be assessed, as well as the development of additional indices and biomarkers that can be derived by combining different new and/or traditional sleep monitoring methods. The large number of patients and wide variety of sleep disorders will make the SOMNIA database a valuable source for a broad range of studies on sleep monitoring and diagnostics.

Focus on diverse pathologies and comorbidities

Currently, there are several sleep databases available. For example, the Wisconsin Sleep Cohort (WSC),⁴³ the Sleep Heart Health study (SHHS)⁴⁴ and the Siesta database.⁴⁵ Both the WSC (n=1500) and SHHS (n=6600) are large population-based studies with a special focus on sleep-disordered breathing. The Siesta database is smaller and

contains PSGs of 194 healthy subjects and 98 patients. The advantage of the SOMNIA database over the existing studies is that it is completely focused on patient data and all primary sleep disorders will be represented.

The SOMNIA data are acquired in a tertiary care referral centre, where a wide variety of (rare) sleep disorders are diagnosed and treated. By integrating research into regular care, it is possible to include a large number of patients with various sleep disorders. All experimental techniques are non-invasive and non-minimally or minimally obtrusive. The study requires no extra visits for the patient outside their regular care. Consequently, this study comprises no extra burden for the patient and almost all patients are eligible for participation. Also complex patients with multiple sleep disorders or comorbidities such as Parkinson's disease, psychiatric or cardiovascular disorders will be included. For specific (combinations of) rare sleep disorders, it might be challenging to include large sample sizes in SOMNIA. However, it is important to have data from these patients available for validation studies aiming towards the general sleep clinic population. This allows validation of new techniques in a 'real-world' clinical setting with its inherent variability and complexity. Furthermore, it provides the opportunity to study the influence of comorbid (sleep) disorders. For example, comorbid insomnia and OSA are gaining attention.^{46 47} However, in datasets collected in population studies or second-line sleep clinics, there are limited data available on this comorbid condition. The SOMNIA database can be used to study the (patho)physiology of these complex patients in more detail.

Unobtrusive sensing technologies

Despite the technical revolution of the past decades, sleep medicine and sleep research still rely on relatively cumbersome diagnostic tools. For example, the diagnosis of OSA relies on several sensors to characterise the nature of sleep-disordered breathing. Measurements of respiration, nasal pressure, blood-oxygen saturation and respiratory effort are typical parts of the standard PSG montage. Respiration is the result of muscle activity that induces negative intrathoracic pressure and expansion of the thoracic and abdominal cavities. Therefore, respiratory effort may be recorded from mechanical, electrical and electromechanical signals.²³ The revised manual for the scoring of sleep and associated events by the AASM recommends the use of oesophageal manometry or dual thoracoabdominal respiratory inductance plethysmography for this purpose.⁵ Especially, the first is an unpleasant procedure, which is often not very well tolerated by patients.⁴⁸ Modern, less invasive sensing technologies such as wrist-worn reflective PPG, snoring analyses, diaphragm EMG and suprasternal pressure measurement all have the potential to capture respiratory characteristics of OSA specifically, and in general, physiological characteristics that might aid in the diagnosis, treatment and follow-up of sleep disorders. However, validation in a real-world clinical setting is

limited and the usefulness of these sensors in clinical practice remains unproven. These aspects are important because devices and algorithms that are developed for healthy users are not readily applicable to patients with sleep disturbances.²²

Children

Paediatric sleep medicine is a young field of research and not many large-scale studies are available. We will make a specific effort to also include a significant number of children in the SOMNIA database. There are essential differences between paediatric and adult patients. In children, other sleep disorders occur and sleep disorders can present themselves in a different way. For example, children do tend to have clinical symptoms of OSA with a much lower Apnoea Hypopnoea Index compared with adults.⁴⁹ Moreover, obstructive events in children occur primarily during REM sleep.⁵⁰ If an insufficient amount of REM sleep is captured during a PSG, for example, due to sleep disruption because of the uncomfortable monitoring equipment, the degree of OSA is likely to be underestimated. So, for this challenging group of patients, it is even more important to develop sleep monitoring techniques that are less obtrusive and intimidating. Furthermore, age is not only a determining factor in how long people sleep, it also has large influence on PSG characteristics, which is reflected in dedicated scoring rules for children and adolescents.¹³ Algorithms developed for analysis of adult sleep should be tested and probably adapted for the paediatric population. Although the sample sizes for paediatric patients will be much smaller than for adults, results from the SOMNIA database could give an indication for the potential usefulness of new non-obtrusive technologies or of adapted analysis algorithms. These could then be further validated in dedicated future studies, including directed efforts to obtain reference data.

In conclusion, with the SOMNIA project, we are creating a neurological database for advanced sleep monitoring in a clinical setting. The data can be used for a broad spectrum of studies, ranging from innovative PSG analyses to the validation of experimental sleep monitoring devices.

ETHICS AND DISSEMINATION

Ethics approval and consent to participate

According to the Dutch directives on research in human subjects, the study was reviewed by the medical ethical committee of the Maxima Medical Center (Eindhoven, the Netherlands, File no: N16.074). The study protocol was approved by the internal review boards of both the Kempenhaeghe Sleep Center (Heeze, the Netherlands) and Philips Research (Eindhoven, the Netherlands).

All subjects provide informed consent before participation. For the children, the information is given to the child as well as the parents (or legal guardians). Informed consent by both parents (or legal guardians) and children (age ≥12 years) is required in order to enter the study.

Availability of data and materials

The SOMNIA database is built to facilitate future research in sleep medicine. Data from the completed SOMNIA database will be made available for collaboration with researchers outside the institute. To get access to the data, a researcher must submit a research protocol, with a clear scientific question, to the Kempenhaeghe Center for Sleep Medicine. An internal review board will review the data request. When the study fits the vision of the SOMNIA project, the researcher will receive a pseudonymised copy of the requested data, to be used in that specific study. Specific restrictions apply to the availability of the data from the wrist-worn PPG sensor (Philips) and optical pressure sensor (2M Engineering), which are used under license and are not publicly available. These data are however available from the authors on reasonable request and with permission of Philips or 2M Engineering.

When the study is finished, the researcher returns the data. Kempenhaeghe will store the original dataset for at least 15 years.

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Contributors MMvG designed the study, arranged the data collection and drafted the manuscript. JPVd was involved in the study design and in writing the manuscript. RK designed the database. BH managed the data collection. PF, RJGvS, BA, NV, TL, CL, HM, RH, JWMB and LvdH assisted with implementing the experimental technologies. NV, SP and DP provided clinical expertise for the study design. SO conceived and supervised the study, was involved in the study design and in writing the manuscript. All authors read and approved the final manuscript.

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REFERENCES

- 1 Berger H. Über das Elektrenkephalogramm des Menschen. *Archiv für Psychiatrie und Nervenkrankheiten* 1929;87:527–70.
- 2 Loomis AL, Harvey EN, Hobart G. Further observations on the potential rhythms of the cerebral cortex during sleep. *Science* 1935;82:198–200.
- 3 Aserinsky E, Kleitman N. Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science* 1953;118:273–4.
- 4 American Academy of Sleep Medicine. *International classification of sleep disorders*. 3rd edn, 2014.
- 5 Berry R, Brooks R, Gamaldo C. *The AASM manual for the scoring of sleep and associated events: rules, terminology and technical specifications version 2*. 2nd edn. Darien, Illinois: American Academy of Sleep Medicine, 2015.
- 6 Pombo N, Garcia N, Bousson K. Classification techniques on computerized systems to predict and/or to detect apnea: a systematic review. *Comput Methods Programs Biomed* 2017;140:265–74.
- 7 Varon C, Caicedo A, Testelmans D, et al. A novel algorithm for the automatic detection of sleep apnea from Single-Lead ECG. *IEEE Trans Biomed Eng* 2015;62:2269–78.
- 8 Babaeizadeh S, White DP, Pittman SD, et al. Automatic detection and quantification of sleep apnea using heart rate variability. *J Electrocardiol* 2010;43:535–41.
- 9 Wetter TC, Dirlich G, Streit J, et al. An automatic method for scoring leg movements in polygraphic sleep recordings and its validity in comparison to visual scoring. *Sleep* 2004;27:324–8.
- 10 Kempfner J, Jennum P, Nikolic M, et al. Automatic detection of REM sleep in subjects without atonia. *Conf Proc IEEE Eng Med Biol Soc* 2012;2012:4242–5.
- 11 Bragazzi NL, Guglielmi O, Garbarino and S. SleepOMICS: how big data can revolutionize sleep science. *Int J Environ Res Public Health* 2019;16:291.
- 12 Newell J, Mairesse O, Verbanck P, et al. Is a one-night stay in the lab really enough to conclude? First-night effect and night-to-night variability in polysomnographic recordings among different clinical population samples. *Psychiatry Res* 2012;200:795–801.
- 13 Grigg-Damberger M, Gozal D, Marcus CL, et al. The visual scoring of sleep and arousal in infants and children. *J Clin Sleep Med* 2007;3:201–40.
- 14 Van de Water ATM, Holmes A, Hurley DA. Objective measurements of sleep for non-laboratory settings as alternatives to polysomnography—a systematic review. *J Sleep Res* 2011;20:183–200.
- 15 Ancoli-Israel S, Cole R, Alessi C, et al. The role of actigraphy in the study of sleep and circadian rhythms. *Sleep* 2003;26:342–92.
- 16 Sadeh A. The role and validity of actigraphy in sleep medicine: an update. *Sleep Med Rev* 2011;15:259–67.
- 17 Willemen T, Van Deun D, Verhaert V, et al. An evaluation of cardiorespiratory and movement features with respect to sleep-stage classification. *IEEE J Biomed Health Inform* 2014;18:661–9.
- 18 Fonseca P, Long X, Radha M, et al. Sleep stage classification with ECG and respiratory effort. *Physiol Meas* 2015;36:2027–40.
- 19 Fonseca P, Weyse T, Goelema MS, et al. Validation of Photoplethysmography-Based sleep staging compared with polysomnography in healthy middle-aged adults. *Sleep* 2017;40:1093/sleep/zsx097. [Epub ahead of print: 01 Jul 2017].
- 20 Willemen T, Varon C, Dorado AC, et al. Probabilistic cardiac and respiratory based classification of sleep and apneic events in subjects with sleep apnea. *Physiol Meas* 2015;36:2103–18.
- 21 Redmond SJ, Heneghan C. Cardiorespiratory-based sleep staging in subjects with obstructive sleep apnea. *IEEE Trans Biomed Eng* 2006;53:485–96.
- 22 Fonseca P, den Teuling N, Long X, et al. A comparison of probabilistic classifiers for sleep stage classification. *Physiol Meas* 2018;39:055001.
- 23 Vandenbussche NL, Overeem S, van Dijk JP, et al. Assessment of respiratory effort during sleep: esophageal pressure versus noninvasive monitoring techniques. *Sleep Med Rev* 2015;24:28–36.
- 24 Walsh L, Moloney E, McLoone S. Identification of nocturnal movements during sleep using the non-contact under mattress bed sensor. *Conf Proc IEEE Eng Med Biol Soc* 2011;2011:1660–3.
- 25 Punjabi NM. The epidemiology of adult obstructive sleep apnea. *Proc Am Thorac Soc* 2008;5:136–43.
- 26 Parish JM, Somers VK. Obstructive sleep apnea and cardiovascular disease. *Mayo Clin Proc* 2004;79:1036–46.
- 27 Calvin AD, Albuquerque FN, Lopez-Jimenez F, et al. Obstructive sleep apnea, inflammation, and the metabolic syndrome. *Metab Syndr Relat Disord* 2009;7:271–7.
- 28 Johns MW. A new method for measuring daytime sleepiness: the Epworth Sleepiness scale. *Sleep* 1991;14:540–5.
- 29 Buysse DJ, Reynolds CF, Monk TH, et al. The Pittsburgh sleep quality index: a new instrument for psychiatric practice and research. *Psychiatry Res* 1989;28:193–213. 3rd.
- 30 Morin CM, Belleville G, Bélanger L, et al. The insomnia severity index: psychometric indicators to detect insomnia cases and evaluate treatment response. *Sleep* 2011;34:601–8.
- 31 Zigmond AS, Snaith RP. The hospital anxiety and depression scale. *Acta Psychiatr Scand* 1983;67:361–70.
- 32 Bültmann U, de Vries M, Beurskens AJ, et al. Measurement of prolonged fatigue in the working population: determination of a cutoff point for the checklist individual strength. *J Occup Health Psychol* 2000;5:411–6.
- 33 Arnulf I, Zhang B, Uguccioni G, et al. A scale for assessing the severity of arousal disorders. *Sleep* 2014;37:127–36.
- 34 American Academy of Sleep Medicine. *International classification of sleep disorders*. 2nd ed, 2005.
- 35 Papini GB, Fonseca P, Aubert XL, et al. Photoplethysmography beat detection and pulse morphology quality assessment for signal reliability estimation. *Conf Proc IEEE Eng Med Biol Soc* 2017;2017:117–20.
- 36 Papini GB, Fonseca P, Eerikainen LM, et al. Sinus or not: a new beat detection algorithm based on a pulse morphology quality index to extract normal sinus rhythm beats from wrist-worn photoplethysmography recordings. *Physiol Meas* 2018;39:115007.
- 37 Paalasmaa J, Waris M, Toivonen H, et al. Unobtrusive online monitoring of sleep at home. *Conf Proc IEEE Eng Med Biol Soc* 2012;2012:3784–8.
- 38 Tenhunen M, Elomaa E, Sistonen H, et al. Emfit movement sensor in evaluating nocturnal breathing. *Respir Physiol Neurobiol* 2013;187:183–9.
- 39 Hirshkowitz M, MH K. Monitoring techniques for evaluating suspected sleep-disordered breathing. In: Kryger MH, Roth T, WC D, eds. *Principles and practice of sleep medicine*. 5th edn. St. Louis, MO, USA: Elsevier Saunders, 2011: 1610–23.
- 40 Maarsingh EJ, van Eykern LA, Sprickelman AB, et al. Respiratory muscle activity measured with a noninvasive EMG technique: technical aspects and reproducibility. *J Appl Physiol* 2000;88:1955–61.
- 41 Meslier N, Simon I, Kouatchet A, et al. Validation of a suprasternal pressure transducer for apnea classification during sleep. *Sleep* 2002;25:753–7.
- 42 Biosemi. Available: https://www.biosemi.com/faq/file_format.htm
- 43 Young T, Palta M, Dempsey J, et al. Burden of sleep apnea: rationale, design, and major findings of the Wisconsin sleep cohort study. *WMJ* 2009;108:246–9.
- 44 Quan SF, Howard BV, Iber C, et al. The sleep heart health study: design, rationale, and methods. *Sleep* 1997;20:1077–85.
- 45 Klösch G, Kemp B, Penzel T, et al. The SIESTA project polygraphic and clinical database. *IEEE Eng Med Biol Mag* 2001;20:51–7.
- 46 Cho YW, Kim KT, Moon H-J, et al. Comorbid insomnia with obstructive sleep apnea: clinical characteristics and risk factors. *J Clin Sleep Med* 2018;14:409–17.
- 47 Luyster FS, Buysse DJ, Strollo PJ. Comorbid insomnia and obstructive sleep apnea: challenges for clinical practice and research. *J Clin Sleep Med* 2010;6:196–204.
- 48 Woodson BT, Wooten MR. A multisensor solid-state pressure manometer to identify the level of collapse in obstructive sleep apnea. *Otolaryngol Head Neck Surg* 1992;107:651–6.
- 49 Marcus CL. Sleep-disordered breathing in children. *Curr Opin Pediatr* 2000;12:208–12.
- 50 Goh DY, Galster P, Marcus CL. Sleep architecture and respiratory disturbances in children with obstructive sleep apnea. *Am J Respir Crit Care Med* 2000;162:682–6.