

REVIEW ARTICLE



The Sleep Revolution project: the concept and objectives

Erna S. Arnardóttir^{1,2} | Anna Sigríður Islind^{1,3} | María Óskarsdóttir^{1,3} |
 Kristín A. Ólafsdóttir¹ | Elias August^{1,4} | Lára Jónasdóttir¹ |
 Harald Hrubos-Strøm^{5,6} | Jose M. Saavedra^{1,7} | Ludger Grote⁸ | Jan Hedner⁸ |
 Sveinbjörn Höskuldsson⁹ | Jón Skírniir Ágústsson⁹ | Kamilla Rún Jóhannsdóttir^{1,10} |
 Walter T. McNicholas¹¹ | Dirk Pevernagie^{12,13} | Reijo Sund¹⁴ |
 Juha Töyräs^{14,15,16} | Timo Leppänen^{14,15,17} | on behalf of the Sleep Revolution

¹Reykjavik University Sleep Institute, Reykjavik University, Reykjavik, Iceland

²Landsþítali University Hospital, Reykjavik, Iceland

³Department of Computer Science, Reykjavik University, Reykjavik, Iceland

⁴Department of Engineering, Reykjavik University, Reykjavik, Iceland

⁵Department of Otorhinolaryngology, Akershus University Hospital, Lørenskog, Norway

⁶Institute of Clinical Medicine, University of Oslo, Oslo, Norway

⁷Physical Activity, Physical Education, Sport and Health (PAPEH) Research Group, Department of Sports Science, Reykjavik University, Reykjavik, Iceland

⁸Internal Medicine, Center for Sleep and Wake Disorders, University of Gothenburg Sahlgrenska Academy, Gothenburg, Sweden

⁹Nox Research, Nox Medical ehf, Reykjavik, Iceland

¹⁰Department of Psychology, Reykjavik University, Reykjavik, Iceland

¹¹Department of Respiratory and Sleep Medicine, St. Vincent's Hospital Group, School of Medicine, University College Dublin, Dublin, Ireland

¹²Respiratory Diseases, University Hospital Ghent, Ghent, Belgium

¹³Department of Internal Medicine and Paediatrics, Ghent University, Ghent, Belgium

¹⁴Department of Applied Physics, University of Eastern Finland, Kuopio, Finland

¹⁵School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Queensland, Australia

Summary

Obstructive sleep apnea is linked to severe health consequences such as hypertension, daytime sleepiness, and cardiovascular disease. Nearly a billion people are estimated to have obstructive sleep apnea with a substantial economic burden. However, the current diagnostic parameter of obstructive sleep apnea, the apnea-hypopnea index, correlates poorly with related comorbidities and symptoms. Obstructive sleep apnea severity is measured by counting respiratory events, while other physiologically relevant consequences are ignored. Furthermore, as the clinical methods for analysing polysomnographic signals are outdated, laborious, and expensive, most patients with obstructive sleep apnea remain undiagnosed. Therefore, more personalised diagnostic approaches are urgently needed. The Sleep Revolution, funded by the European Union's Horizon 2020 Research and Innovation Programme, aims to tackle these shortcomings by developing machine learning tools to better estimate obstructive sleep apnea severity and phenotypes. This allows for improved personalised treatment options, including increased patient participation. Also, implementing these tools will alleviate the costs and increase the availability of sleep studies by decreasing manual scoring labour. Finally, the project aims to design a digital platform that functions as a bridge between researchers, patients, and clinicians, with an electronic sleep diary, objective cognitive tests, and questionnaires in a mobile application. These ambitious goals will be achieved through extensive collaboration between 39 centres, including expertise from sleep medicine, computer science, and industry and by utilising tens of thousands of retrospectively and prospectively collected sleep recordings. With the commitment of the European Sleep Research Society and Assembly of National Sleep Societies, the Sleep Revolution has the unique possibility to create new standardised guidelines for sleep medicine.

¹⁶Science Service Center, Kuopio University Hospital, Kuopio, Finland

¹⁷Diagnostic Imaging Center, Kuopio University Hospital, Kuopio, Finland

Correspondence

Erna S. Arnardottir, Reykjavik University, Menntavegi 1, 102 Reykjavik, Iceland.
Email: ernasifa@ru.is

KEYWORDS

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THE OBJECTIVES OF THE SLEEP REVOLUTION

Sleep Revolution's consortium, consisting of 39 partners from Europe and Australia, combines multidisciplinary competencies and resources from academia, healthcare, and industry. The consortium has good geographical and cultural coverage across Europe.

The Sleep Revolution, which is funded by European Union's Horizon 2020 Research and Innovation Programme, aims to fundamentally change clinical sleep medicine for sleep-disordered breathing (SDB) by introducing a new diagnostic and digital management paradigm. The paradigm developed combines the highest degree of diagnostic accuracy possible for detecting SDB, from habitual snoring to severe obstructive sleep apnea (OSA), with diagnostics in the home setting instead of the artificial sleep environment in a hospital. Moreover, advanced telemedicine technology, novel machine learning (ML) algorithms for diagnosis, and a high degree of participatory patient involvement are combined in three clinical studies.

The aim is for patients to self-administer their sleep studies and sleep at home for multiple nights with diagnostic equipment. The latest innovations in telemedicine are employed to provide comprehensive information on wellbeing, symptom burden, treatment adherence through self-reported questionnaires, continuous monitoring of biosignals via wearables, and objective cognitive testing (Arnardottir et al., 2021). All clinically relevant information and sleep study results are available to the patient, emphasising the importance of participatory healthcare. The data are transferred to a central data store and displayed in a digital management platform (DMP) with secure and controlled access to the patient/research subject and relevant healthcare professionals and research staff. Novel algorithms utilising ML provide sleep parameters with high diagnostic precision and significantly enhanced predictive value for patient-related outcome measures (PROMs) compared to current clinical practice (Pevernagie et al., 2021).

Individuals with SDB constitute the primary target population of the Sleep Revolution because of the substantial unmet medical need for improved diagnostic solutions and management techniques worldwide (Benjafield et al., 2019). There is, therefore, an urgent need for digital technology, diagnostic solutions, and computational algorithms that go beyond the current state-of-the-art. Currently, several significant drawbacks exist in clinical decision-making and management of SDB: (i) outdated diagnostic criteria for OSA, (ii) expensive in-laboratory diagnostic procedures or limited home sleep apnea testing (HSAT), (iii) limited participatory healthcare, and (iv) lack of preventive intervention approaches. The Sleep Revolution project addresses

these fundamental drawbacks of the current approach, explained in detail below.

Objective 1: transform current diagnostic methods for SDB

The current diagnostic criteria for OSA are defined in terms of the number of breathing cessations (apneas) and breathing reductions (hypopneas) per hour of sleep, the so-called apnea–hypopnea index (AHI). The clinical diagnosis of OSA is based on cut-off limits of the AHI, where $AHI \geq 15$ events/h is considered a moderate–severe disease and $5 \leq AHI < 15$ events/h with the presence of excessive daytime sleepiness (EDS) or comorbidities as a mild disease (Berry et al., 2014, 2020). However, the AHI gives no attention to the physiological and neurobehavioural impacts on the patient. Furthermore, the AHI is an outdated measure, and it is poorly associated with important SDB-related PROMs and adverse health outcomes: symptoms, comorbidities, and survival (Pevernagie et al., 2021).

Many sensors measuring an array of physiological signals are included in the “gold standard” polysomnography (PSG) and analysed manually in an expensive and laborious process. This process does not account for most information embedded in the recorded signals but reduces the data into one over-simplistic index, the AHI (Berry et al., 2020). This has several significant shortcomings, significantly limiting the estimation of the actual severity of SDB.

Our field has the urgent and significant task of defining relevant disease characteristics beyond the AHI. In the Sleep Revolution, we will update the current SDB diagnostics methods developed in the 1970s for paper records. We will accomplish this by developing personalised SDB diagnostic parameters that predict future adverse health consequences and determine treatment needs in a patient-specific manner. This includes an in-depth assessment of the duration of respiratory events, the pattern of hypoxic burden during sleep, the level of sleep fragmentation, as well as the sympathetic and cardiovascular response to SDB events (Azarbarzin et al., 2019; Kainulainen, Duce, et al., 2020; Kainulainen, Töyräs, et al., 2020; Korkalainen et al., 2021; Kulkas et al., 2013; Muraja-Murro et al., 2013, 2014).

We are taking advantage of the huge retrospective sleep study data pool, with tens of thousands of sleep recordings and relevant health information already gathered by our strong network of

partners from all over Europe. Modern ML and signal processing techniques are being applied to this vast pool of retrospective data. A vital outcome of the Sleep Revolution is improved knowledge about which signals should be assessed, sampled, and analysed in a sleep study to provide state-of-the-art diagnostic parameters for SDB. In particular, novel diagnostic concepts need to address the different dimensions described in Figure 1. This is of critical importance to prevent severe health consequences for those most in need, for individualising their treatment, and for targeting the limited treatment resources to them. Also, overtreatment of patients, who benefit less from the intervention, can be better avoided by employing these more sophisticated diagnostic parameters valid in all three dimensions “A” (respiratory events), “E” (acute systemic effect), and “O” (chronic end-organ impact) (Pevernagie et al., 2020; Randerath et al., 2018).

A lack of standards for evaluating medical data for proper diagnosis and follow-up of patients constitutes a highly significant unmet need. Moreover, clinical sleep scoring involves a tedious visual review of overnight polysomnograms by an expert, a suitable task for modern ML algorithms. Indeed, ML algorithms have been applied to sleep scoring for many years. As a result, today, several software products offer automated or semi-automated scoring services. Deep learning has also been employed, clearly demonstrating the opportunity to overcome the limitations of automatic analysis of sleep recordings. It is already the position of the American Academy of Sleep Medicine that deep learning is expected to improve sleep laboratory efficiency and yield more significant clinical insights (Goldstein et al., 2020). Hopefully, automatic analysis will replace manual scoring very soon; however, currently, this is not accepted by clinical standards. To this end, Sleep Revolution aims to revolutionise the diagnosis of SDB by providing a new European Sleep Scoring Manual. This will include detailed research-based guidelines for the diagnostic procedure: what to measure, how to measure, how to analyse, and with which criteria. The aim is to provide tailored and personalised treatment to maximise benefits for patients using automatic scoring procedures when possible and overcome many of the limitations of current scoring methods (Arnardottir et al., 2016).

As sleep recordings are now digitised, there is no need to be restricted by practical constraints as it was in the 1970s when sleep recordings were paper based. To overcome these limitations, we have already started to develop ML-based methods to analyse sleep studies and estimate the severity of OSA and related daytime symptoms (Huttunen et al., 2021; Korkalainen et al., 2019; Nikkonen et al., 2019, 2020, 2021). Moreover, we will continue this work and produce fully-automated deep-learning-based analysis algorithms for PSGs and HSATs using state-of-the-art methods such as convolutional neural networks and recurrent neural networks. Deep-learning-based solutions will be developed to track novel biomarkers from PSG signals that could be used to determine OSA severity linked to acute systemic effects and chronic end-organ impact (Figure 1). In addition, we will use active learning to feed the expertise of the sleep technologists into our models to further improve the accuracy of the models.

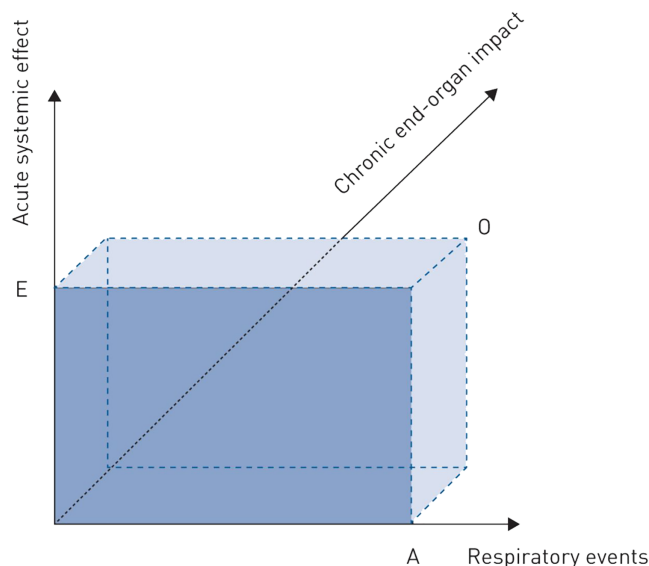


FIGURE 1 Graphic representation of a three-dimensional model of obstructive sleep apnea disease severity. Reproduced with permission from Randerath et al. (2018).

Objective 2: to bring advanced sleep diagnostics from the hospital into the patient's home

The “gold standard” diagnostic method for SDB is an in-hospital PSG with patients sleeping 1 night in the hospital. The professional workload is the following: patient admittance (1 h), equipment hook-up and disconnecting (1.5 h), attended PSG (8 h of monitoring), manual scoring (1.5 h), medical doctor (1 h), a total of 13 h of work (Fischer et al., 2012). However, many experienced sleep-technologists state that manual scoring generally takes 2–3 h, and even longer for complex cases. Furthermore, there may be significant inter-scorer variability, even among experienced technologists. Therefore, performing a sleep study is expensive, often with long waiting lists due to the high work demand on expert staff. Additionally, this form of diagnosis is uncomfortable for the patient and may not represent their regular sleep pattern at home due to sleeping in an unfamiliar setting with many sensors attached.

The current solution to this lack of resources is HSAT (Berry et al., 2020), which is now widely adopted to promptly provide patient care (Arnardottir et al., 2016). A significant drawback of this development in Europe and worldwide is its lack of diagnostic accuracy as the measurement of sleep quality (sleep stages and sleep fragmentation) cannot be done except by proxy due to the lack of electroencephalography measurement. This causes a major loss of diagnostic quality in HSAT studies.

Sleep Revolution is overcoming this major limitation by validating self-applied PSG against the “gold standard” PSG (Kainulainen et al., 2021). Instead of the traditional 1-night PSG or HSAT, the Sleep Revolution utilises a 3-night diagnostic procedure with self-applied PSG (Figure 2). This multiple-night setup addresses the important issue of night-night variability in SDB severity and the first night

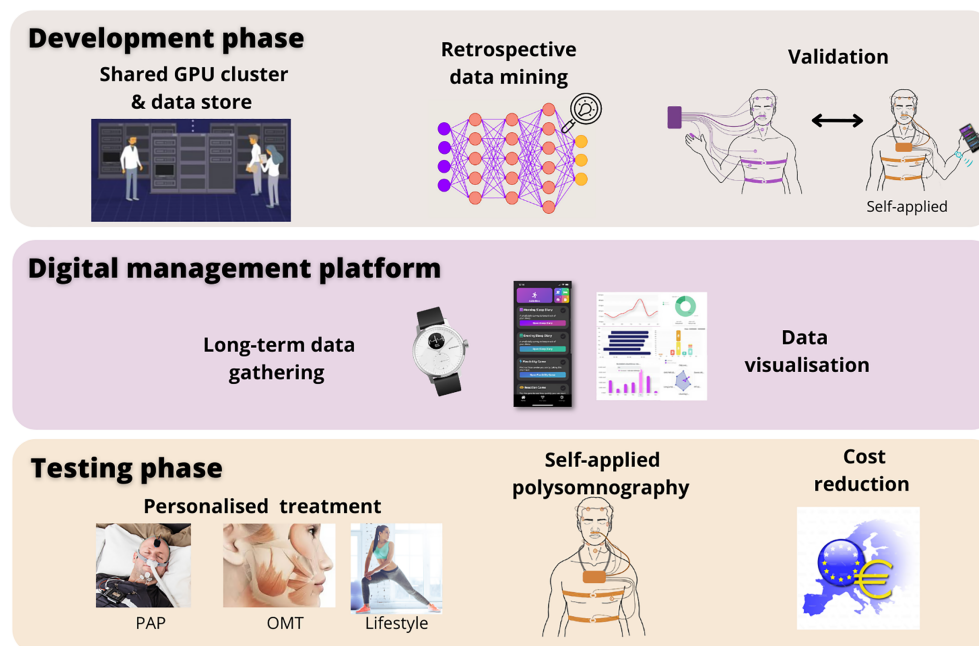


FIGURE 2 The sleep revolution concept, the digital management platform functions as a bridge between development and testing. GPU, graphics processing unit; OMT, oromyofunctional therapy; PAP, positive airway pressure

effect of sleeping with the equipment (Gouveris, et al., 2010; Sforza et al., 2019). Together with validated automated scoring tools, this new sleep diagnostic technology allows the combination of the highest diagnostic quality with easy access and lower costs. This will make diagnosis and management of SDB more cost-effective, less intrusive and, thus, more widespread.

If utilised with new wearables (e.g., self-applied PSG coupled with an actigraphy used for a longer period), this type of sleep evaluation could be potentially applied across all hospital settings, not only to estimate the quality of sleep for patients with SDB, but also to ensure that the sleep is assessed efficiently, cost-effectively, and in a standardised way, potentially allowing for long-term assessment of sleep (Óskarsdóttir et al., 2022).

Objective 3: to promote participatory healthcare with technological solutions

“4P medicine” is defined as predictive, preventive, personalised, and participatory medicine (Figure 3). It aims to quantify wellness and to predict and prevent disease by combining medicine, digital technologies, and consumer-driven healthcare (Flores et al., 2013). It goes hand in hand with the current trend toward automatisisation and increased digitalisation, where readiness and transparency of data play an important role.

The current clinical management of SDB offers patients limited personalised and participatory healthcare options. In some countries, patients can monitor their positive airway pressure (PAP) treatment adherence via their manufacturer's device and software (Malhotra et al., 2018). Also, the healthcare provider can change the settings on the PAP device for increased performance remotely. However, all other treatment decisions and follow-up conversations occur through

physical visits to the hospital/sleep centre or by telephone. No attempts have been previously made to collect and present the large variety of sleep data in one DMP.

In the Sleep Revolution, we have designed a DMP via co-design (Islind et al., 2019). The DMP is a state-of-the-art digital platform that acts as a bridge between the research participants (patients), healthcare professionals, and researchers (Figure 4). The majority of the data collection in our studies occurs remotely via the DMP. The DMP is accessible to the research participant through a smartphone and a tablet as well as via a web browser. Furthermore, we have designed and developed a mobile application (an app) that feeds data into the DMP. The app enables the collection of objective cognitive tests, subjective morning and evening sleep diary, and specific events during the day. The DMP visualises the data from the research participants and includes continuous measurements of PROMs, data from PSG, smartwatches, anthropometric and comorbidity data, as well as the data from the objective cognitive tests and the sleep diaries based on the Consensus Sleep Diary (Carney et al., 2012). That data flows into the DMP, enabling long-term monitoring and P4 medicine. Standardised calculations based on the diary, smartwatches, and self-applied PSG will also be presented for all three abovementioned stakeholder groups via the DMP. A new neurocognitive test battery is being generated as a part of the Sleep Revolution project (Jóhannsdóttir et al., 2021). Neurocognitive testing serves as an essential objective tool for assessing a patient's daytime functioning and, along with other measures, can assess individuals' status and monitor their progress throughout treatment. To date, there is no standard battery of neurocognitive tests in the SDB field, making it difficult to determine which tests to use. Jóhannsdóttir et al. (2021) proposed a large comprehensive battery, including neurocognitive tests targeting a broad range of cognitive domains and subdomains and functions. A smaller, more focussed test battery is implemented

FIGURE 3 Entering into the era of P4 medicine, where the focus is to predict, prevent, personalise, and enable participation.

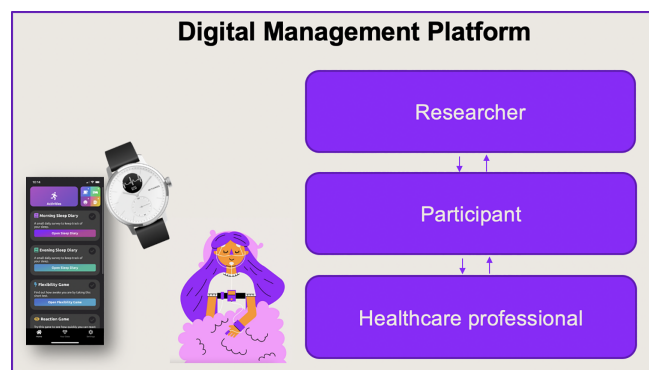
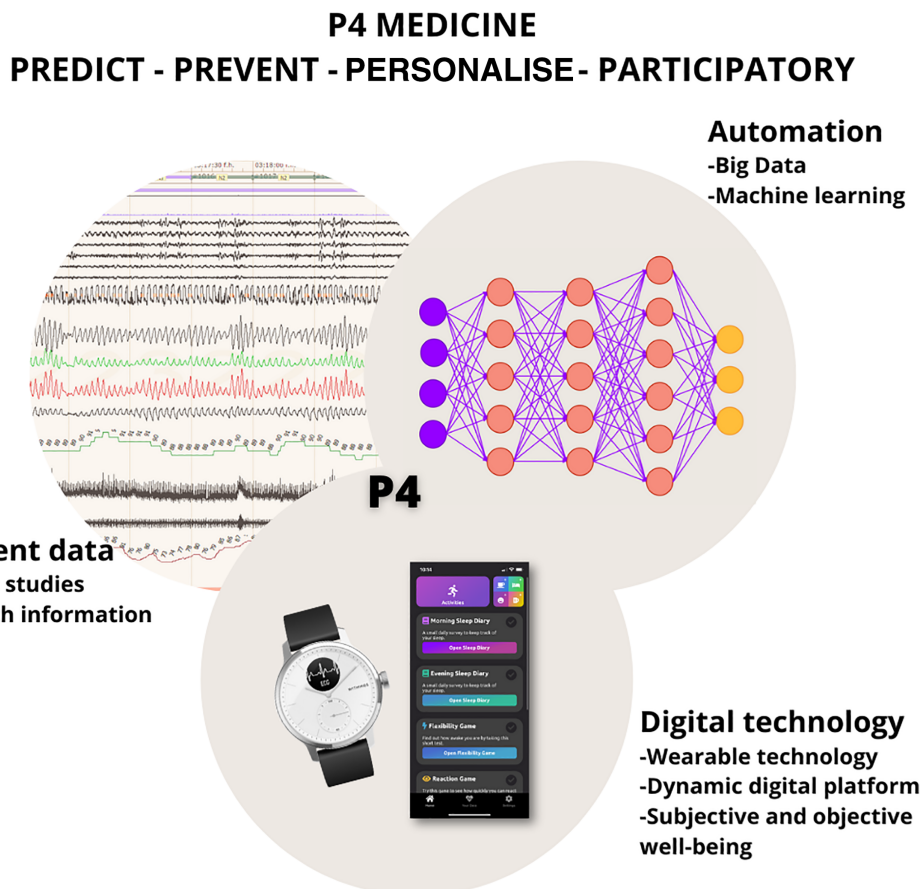


FIGURE 4 The digital management platform, connecting researchers, participants, and healthcare professionals.

in the app and the DMP. These tests in the app mainly address vigilance and sustained attention and aspects of executive functions, as these are the two most affected domains in SDB. For example, a 3-min version of the electronic psychomotor vigilance task is included to evaluate vigilance and the ability to sustain attention (Dinges & Powell, 1985; Grandner et al., 2018). The research participants can then receive feedback on their performance in real-time.

Treatment by participatory medicine principles is also delivered in the DMP on modules tailored for personalised treatment options presented below. The modules consist of exercise diaries, instruction videos, and motivational support tools such as reminders and rewards.

Furthermore, we are generating a new European Sleep Questionnaire with PROMs at the forefront, which will be validated in the testing phase of Sleep Revolution. Because of the non-specificity of symptoms and overlapping characteristics of nosologically defined sleep disorders such as an integrative approach seems quintessential. This instrument could be used for multiple goals, including diagnosis of various sleep disorder phenotypes, identifying treatable traits, and evaluating the effects of treatment assessed by practitioners and patients alike. The latter aspect opens perspectives for designing new and better PROMs. As with sleep questionnaires, currently available PROM forms are narrowly focussed and may probe only part of the health-related quality-of-life aspects that matter to patients (Pevernagie et al., 2021). The development of PROMs also requires a more holistic approach. The European Sleep Questionnaire will be designed so that its metric is sensitive to change induced by treatment (or the natural course of the disease).

To summarise, the co-designed DMP allows 4P medicine in practice on a much larger and more complex scale than previously possible, promoting participatory healthcare with technological solutions.

Objective 4: develop different personalised treatment options for patients with SDB

Current clinical standards for SDB treatment lack personalised and preventive treatment approaches that address the SDB causes,

e.g., obesity, physical inactivity, and poor upper airway muscle function (Myers et al., 2013). There is broad consensus that treatment with PAP is the first line of treatment for moderate–severe OSA, while other treatment options still need to be validated further in future studies (Randerath et al., 2021). We are developing and validating two personalised treatment options for patients with SDB that require their active participation in Sleep Revolution. These treatment modalities are oromyofunctional therapy (OMT) (Rueda et al., 2020) and lifestyle intervention (exercise programme). The overall goal is to offer alternative treatment options aside from PAP for suitable patient groups and to prevent worsening of mild–moderate OSA into severe disease.

In the Sleep Revolution, a multicentric randomised controlled trial (RCT), including a PAP treatment follow-up study, will be performed for patients with OSA by the European Sleep Apnea Database (ESADA) network (Bonsignore et al., 2018). This is a verification trial for many innovations obtained in the Sleep Revolution project. The following components will be evaluated:

- A. Application of Sleep Revolution sleep diagnostic technology (self-applied PSG and wearables).
- B. Automated data download and cloud-based automated sleep analysis using ML and novel European Sleep Scoring criteria.
- C. Patient platform to evaluate the different dimensions of the PROM and the use of the novel European Sleep Questionnaire.
- D. Integration of patient self-management in the digital health platform.

A total of 1,000 patients from 24 European sleep centres will be randomised to local standard care, or the Sleep Revolution managed care model. PROM improvement and PAP compliance are the primary study outcomes to be compared in the RCT.

Recent systematic reviews of the effect of OMT on OSA conclude that OMT as a participatory health intervention is promising as monotherapy in mild–moderate disease and as an adjunct to other therapies in moderate–severe disease. However, the need for further studies is also highlighted due to the small number of studies available, heterogeneity of interventions, and high risk of bias with low quality of evidence (Camacho et al., 2015; Hsu et al., 2020; Mediano et al., 2019). For OMT, a multi-centre RCT will be performed for patients with mild–moderate OSA, which will be again, followed for 3 months. The primary endpoints are adherence to treatment and reduction in OSA severity.

Low levels of physical activity or exercise is associated with moderate–severe OSA (Simpson et al., 2015). Several meta-analyses carried out on the effect of different exercise programmes that have included seven studies or fewer (Aiello et al., 2016; Amiri et al., 2021; Lins-Filho et al., 2020, 2021) and 12 other studies (Mendelson et al., 2018) have shown that the AHI improves after intervention with these exercise programmes. For the lifestyle treatment, the primary endpoints are adherence to treatment and reduction in OSA severity using a lifestyle app versus in-person training in young adults with mild OSA and a sedentary lifestyle (Mendelson et al., 2018; Stavrou et al., 2021).

CONCLUSION

Novel methods for (early) diagnosis and targeted treatment of SDB have great potential for being very beneficial for patients and society as a whole. Usually, patient-level benefits of new technology are understood in terms of improved outcomes and quality of life, but the societal point of view also requires assessment of costs, cost-benefits, and cost-effectiveness. The known direct beneficial mechanisms of new technology for patients include increased treatment adherence and symptoms improvement. Societal benefits will be maximised if the correct patient group is diagnosed early and if the treatment is administered to those in the greatest need. Especially, preventive actions such as getting to people early with health monitoring are likely to reduce the future burden of disease. Thus, to wrap up the results from all the above-mentioned objectives, the Sleep Revolution aims to evaluate how much society and governments in Europe can save with the proposed actions that are targeted toward P4 medicine in SDB management with an emphasis on the use of ML and telemedicine to reduce manual labour and healthcare cost. At the same time, it aims to improve patient participation and personalised treatment options. In summary, the Sleep Revolution is pushing beyond the state-of-the-art and acts as a major player in designing the future of sleep medicine.

AUTHOR CONTRIBUTION

Erna S. Arnardottir provided an outline of the manuscript based on the project. All other authors participated in the conceptualisation and writing of the manuscript and accepted its final version to be submitted.

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CONFLICT OF INTEREST

Erna S. Arnardottir discloses lecture fees from Nox Medical, Philips, ResMed, Jazz Pharmaceuticals, Linde Healthcare, Alcoa Fjardaral, and Wink Sleep. Erna S. Arnardottir is also a member of the Philips Sleep Medicine and Innovation Medical Advisory Board. Jón Skírniir Ágústsson is employed by Nox Medical. Sveinbjörn Höskuldsson is a shareholder and employed by Nox Medical. The other authors have nothing to disclose.

DATA AVAILABILITY STATEMENT

N/A

ORCID

Erna S. Arnardottir  <https://orcid.org/0000-0003-0877-3529>

María Óskarsdóttir  <https://orcid.org/0000-0001-5095-5356>

Ludger Grote  <https://orcid.org/0000-0002-7405-1682>

Walter T. McNicholas  <https://orcid.org/0000-0001-5927-2738>

Dirk Pevernagie  <https://orcid.org/0000-0002-7372-8583>

Reijo Sund  <https://orcid.org/0000-0002-6268-8117>

Timo Leppänen  <https://orcid.org/0000-0003-4017-821X>

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