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Application of portable sleep monitoring devices in pregnancy: a comprehensive review

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Abstract

The physiological, hormonal and biomechanical changes during pregnancy may trigger sleep disordered breathing (SDB) in pregnant women. Pregnancy-related sleep disorders may associate with adverse fetal and maternal outcomes including gestational diabetes, preeclampsia, preterm birth and gestational hypertension. Most of the screening and diagnostic studies that explore SDB during pregnancy were based on questionnaires which are inherently limited in providing definitive conclusions. The current gold standard in diagnostics is overnight polysomnography (PSG) involving the comprehensive measurements of physiological changes during sleep. However, applying the overnight laboratory PSG on pregnant women is not practical due to a number of challenges such patient inconvenience, unnatural sleep dynamics, and expenses due to highly trained personnel and technology. Parallel to the progress in wearable sensors and portable electronics, home sleep monitoring devices became indispensable tools to record the sleep signals of pregnant women at her own sleep environment.

This article reviews the application of portable sleep monitoring devices in pregnancy with particular emphasis on estimating the perinatal outcomes. The advantages and disadvantages of home based sleep monitoring systems compared to subjective sleep questionnaires and overnight PSG for pregnant women were evaluated. An overview on the efficiency of the application of home sleep monitoring in terms of accuracy and specificity were presented for particular fetal and maternal outcomes. Based on our review, more homogenous and comparable research is needed to produce conclusive results with home based sleep monitoring systems to study the epidemiology of SDB in pregnancy and its impact on maternal and neonatal health.

Keywords: Pregnancy, sleep, OSA, portable, monitoring, fetal outcomes, maternal

Introduction

SDB refers to a number of abnormalities characterized by disordered respiratory patterns or peculiar gas exchange during sleep (Hauri, 2011). Both physiological and epidemiological data have suggested that SDB is highly prevalent during pregnancy (Venkata and Venkateshiah, 2009; Bourjeily *et al.*, 2011; Izci-Balserak and Pien, 2010). SDB attributes to a spectrum of abnormal respiratory events ranging from simple snoring up to the most complicated and severe forms such as obstructive sleep apnea (OSA) and upper-airway resistance syndrome (Louis *et al.*, 2014; Pien *et al.*, 2014). There is a growing evidence that the physical, physiological and hormonal alterations triggered by and maintained during pregnancy may place the pregnant women at a risk for the development of SDB (Pien *et al.*, 2014). Moreover, several studies reported that SDB is associated with adverse pregnancy outcomes including gestational hypertensive disorders and gestational diabetes (Luque-Fernandez *et al.*, 2013; Pamidi *et al.*, 2014; Ding *et al.*, 2014; Facco, 2011). All these reports suggest that it is important to monitor, diagnose and manage SDB during pregnancy to prevent SDB induced adverse fetal or neonatal outcomes.

Overnight PSG is the gold standard monitoring tool in diagnosing SDB (Kushida *et al.*, 2005). However, most of the screening and diagnostic studies that explore SDB during pregnancy were based on questionnaires and inherently limited in yielding definite conclusions due to the lack of polysomnographic confirmations (Hukins and Duce, 2022). This is mainly because it is logistically not feasible to apply overnight PSG in practice to all pregnant women considered at high risk for SDB (Flemons *et al.*, 2004). Alternatively, home sleep monitoring devices were frequently employed to facilitate easy screening and diagnosing of SDB with a low cost and time efficient manner in recent years (Berry *et al.*, 2008). This article, for the first time, provides a comprehensive review on the application of home sleep monitoring devices in screening SDB during pregnancy and estimating perinatal outcomes for this population.

Pregnancy as a risk factor for SDB

The underlying cause for the increasing SDB triggered and/or augmented by the pregnancy may be originated due to the individual or cumulative effects of physiological, hormonal, mechanical and cardiovascular changes in the women body (Izci-Balserak and Pien, 2010). Anatomical narrowing and increased upper-airway resistance may occur during the course of pregnancy. This is mainly because of the increased level of estrogen and progesterone levels which induce hyperemia, nasopharyngeal mucosal edema, vasomotor rhinitis and ventilator drive (Hegewald and Crapo, 2011; Dzieciolowska-Baran *et al.*, 2013; Stahl *et al.*, 1985). Therefore, pregnant

women with narrowed upper airways or airway collapse are more likely to be predisposed to SDB such as habitual snoring and OSA compared to non-pregnant women (Izci *et al.*, 2006; Facco, 2011).

Furthermore, late in pregnancy, the enlarging uterus causes diaphragmatic elevation results in tracheal shortening and reduced functional residual capacity (FRC) by 20% (Weinberger *et al.*, 1980). This reduction in FRC can decrease maternal oxygenation and caudal traction of the trachea and pharynx enhancing the collapsibility of the upper airway (Hirnle *et al.*, 2013). All these mechanisms during pregnancy can cause decreased maternal oxygenation that is associated with apnea and hypopnea episodes and compromise the oxygen delivery of the fetus (Awe *et al.*, 1979). Moreover, the progressive weight gain within the course of pregnancy may also predispose women to OSA due to the narrowing in the upper airways including abnormal upper airway structures such as tonsillar and adenoid hypertrophy and macroglossia (Dalfra *et al.*, 2022). Cohort studies of pregnant women demonstrated that high BMI in pregnancy and older age and smoking are high risk factors for SDB (Louis *et al.*, 2012).

Habitual snoring in pregnancy

Snoring is the most common symptom of SDB. Habitual snoring is defined as existence of loud snoring at least three nights per week. Habitual snoring is a risk factor for SDB and several work reported that it is particularly common in pregnant women. In cross-sectional studies, it has been reported that the prevalence of habitual snoring varies between 11.9% and 49% in the third trimester of pregnancy (Bourjeily *et al.*, 2010). Early prospective studies comparing the snoring rate before and after pregnancy reported that the snoring rate increases from 4-14% to 14-28% in the last trimester of pregnancy (Domingo *et al.*, 2006; Izci *et al.*, 2006). In recent longitudinal studies exploring the variation of the severity of habitual snoring in different trimesters of pregnancy, it has been reported that habitual snoring rate of 7-11% in the first trimester increases to 16-25% in the third trimester (Facco *et al.*, 2010b; O'Brien *et al.*, 2012a; Sarberg *et al.*, 2014; Bourjeily *et al.*, 2010).

Many authors have reported that habitual snoring is associated with maternal outcomes such as gestational diabetes (Facco *et al.*, 2010a), gestational hypertension (Franklin *et al.*, 2000; Ursavas *et al.*, 2008) and preeclempsia (O'Brien *et al.*, 2012a). Although there are many work to explore the link between snoring and adverse perinatal outcomes, the literature about the correlation of snoring rate and fetal outcomes is conflicted. In a longitudinal study, O'brein et al reported that rather than the chronic snoring, the snoring triggered by pregnancy as a new- onset has a

significant impact on gestational hypertension and preeclempsia (O'Brien *et al.*, 2012a). In an early work, Loube et al reported that frequent snoring is more often in pregnant than in non-pregnant women (Loube *et al.*, 1996). However, snoring mothers do not appear to be at increased risk for delivering infants with fetal compromises. Supporting this early work, Ayrim et al reported that although there is an increased rate of snoring in pregnant women compared to non-pregnant women, they did not find any effect of this on fetal outcomes (Ayrim *et al.*, 2011). Qiu et al reported that short sleep duration and snoring are associated with glucose intolerance and gestational diabetes mellitus (Qiu *et al.*, 2010). Same findings were reported by Facco et al that short sleep duration and frequent snoring are associated with glucose intolerance in pregnancy (Facco, 2021). Franklin et al reported that snoring is a sign of pregnancy-induced hypertension and indicates a risk of growth retardation of the fetus (Franklin *et al.*, 2000). Micheli et al reported that women with severe snoring in late pregnancy have a higher risk for fetal-growth-restricted neonates and women with sleep deprivation have a high risk for preterm births (Micheli *et al.*, 2011). Tauman et al reported that no differences in maternal characteristics or fetal outcome were found between chronic snorers and news-onset snorers (Tauman *et al.*, 2011). Sharma et al reported that snoring is a high risk factor for gestational hypertension and cesarean delivery (Sharma *et al.*, 2016). Note that all these work studying the snoring in pregnancy were based on questionnaires and used questionnaire outcomes to provide quantitative results about snoring rates. However, providing a highly conclusive result on the potential impact of habitual snoring alone in fetal outcomes is likely complex since the association of other severe SDB disorders particularly OSA should be considered as well.

Obstructive Sleep Apnea in Pregnancy

OSA is a common symptom of SDB particularly in young obese pregnant women (Sahin *et al.*, 2008). The major symptoms of OSA are loud and persistent snoring, cessation in breathing reported by the bed partner and excessive daytime sleepiness. Several authors reported that OSA is linked to cardiovascular diseases, metabolic diseases, poor sleep quality and impaired day-time function (Abbasi *et al.*, 2021). Most studies exploring OSA in pregnancy were based on sleep questionnaires mentioned above which were developed originally for non-pregnant and predominately male populations. Therefore, the exact prevalence of OSA among pregnant women is not known due to the lack of large population-based epidemiological studies using objective sleep measures such as PSG (Bixler *et al.*, 2001). In a questionnaire based study on 220 pregnant women, Olivarez et al reported that the overall prevalence of OSA was 25.4% and increases to 46% among obese pregnant women (Olivarez *et al.*, 2011). In a prospective cohort

study based on PSG recordings on 105 pregnant women, Pien et al reported that 10.5% of the women in the first and 26.7% of women in the third trimester has OSA (Pien *et al.*, 2014). In the same work it is reported that high baseline BMI and maternal age are risk factors for third trimester OSA.

The relationship between the OSA and adverse pregnancy outcomes was also studied by many authors. In a cross-sectional survey study on 1000 women, Bourjeily et al reported that symptoms of OSA are common in pregnancy and associated with a higher likelihood of gestational hypertensive disorders, gestational diabetes and unplanned Caesarean deliveries (Bourjeily *et al.*, 2010). In a case control study Louis et al aimed to estimate the maternal and neonatal morbidities associated with OSA in pregnancy (Louis *et al.*, 2012). They reported that pregnancies associated by OSA are at increased risk for preeclampsia, medical complications, and indicated PTB. In a meta-analysis study, Xu et al reported that OSA in pregnant women significantly increases the incidence of maternal and neonatal outcomes that is associated with more frequent preeclampsia, preterm birth, caesarean delivery, neonatal intensive care unit admission (Xu *et al.*, 2014).

Screening SDB in pregnancy: Polysomnography and sleep questionnaires

Based on the growing literature on the high prevalence of SDB in pregnant population and its association with adverse maternal and perinatal outcomes, early diagnosis of SDB, particularly OSA, is a highly significant challenge in pregnancy. However, number of studies on how often SDB is screened for in pregnancy is rare and accuracy of symptoms for detecting SDB in pregnancy is unclear. In a survey study performed on 776 patients and 80 providers Bourjeily et al reported that less than 3% of providers reported asking about snoring, closely matching patient responses (Bourjeily *et al.*, 2012). Although 32% of patients snored, only 5% were asked about snoring during a prenatal visit. They concluded that the SDB is poorly assessed and underdiagnosed during routine prenatal care.

To date, most of the available research on the sleep dynamics during pregnancy is based on subjective data from screening questionnaires (Mindell *et al.*, 2015). It is a common practice to apply subjective questionnaires of the Berlin Questionnaire and the Epworth Sleepiness Scale [ESS]. In a prospective study evaluating the performance of the Berlin and ESS questionnaires as a screening tool, Facco et al reported that these questionnaires are not reliable predictors of SDB in high-risk pregnant women and some validation studies support the poor predictive ability of questionnaires in pregnancy (Facco *et al.*, 2012). In a prospective trial on OSA study, Olivarez

et al reported that when compared with PSG, sensitivity and specificity by Berlin screening was 35% and 63.8%, respectively implying that the Berlin questionnaire poorly predicts OSA in pregnancy (Olivarez *et al.*, 2010). Although frequent snoring, chronic hypertension, baseline BMI and maternal age may help to pre-diagnose SDB, the questionnaire based studies are far away to draw a definitive and conclusive picture due to the lack of objective sleep measures (Garbazza *et al.*, 2020).

The current gold standard to examine patients' sleep characteristics and to precisely define the sleep macro- and micro-structure is to perform whole night laboratory PSG which involves comprehensive measurement of physiological changes during sleep (Garbazza *et al.*, 2020). However, applying the overnight PSG on all pregnant women who are screened at high risk for SDB is not practical due to a number of challenges including patient inconvenience, a foreign sleep environment, and expenses due to highly trained personnel and technology. To date, there are no large studies that have confirmed a higher prevalence of SDB confirmed by polysomnographic recordings in pregnant population.

Portable sleep monitoring devices

The complicated setup including various sensors, convoluted wires and bulky electronics, low availability and high cost of PSG prevent patients with SDB symptoms from the utility of PSG for precise sleep monitoring. Due to the laboratory environment of PSG, many patients experience difficulties in falling asleep and do not show natural sleep behavior. The need for adapted metrics of "real-world" sleep patterns and monitoring systems have been gradually increasing. This is required mainly to eliminate the above mentioned atypical sleeping environment provided by PSG. Furthermore, it is a common practice to record a single-night snapshot with PSG. However, sleep is a dynamic process that might potentially exhibit varying patterns from day to day and therefore most of the clinical and research oriented work need to measure multiple nights of sleep. This fact is even more prominent during pregnancy because of the increased variability of the physical, physiological and hormonal dynamics. Because each of these pregnancy-triggered dynamics can vary from day to day which might induce complex interactions, large datasets are needed to study correlations with sleep which is not feasible by PSG. Recent progress in wearable sensor technology provides a promising alternative for home sleep monitoring to overcome the challenges with PSG. Recent studies reported that the progress in wearable sensors and portable electronics can enable comfortable and accurate sleep assessment even at home (Kwon *et al.*, 2021).

In a typical portable sleep monitoring device, there exist multiple wearable sensors and specific locations to measure sleep-related signals, including brain activity (EEG), heart activity (ECG), blood oxygenation data (spO2), respiration dynamics, chest and abdominal respiratory movement, body position and snoring. Several blind studies were performed to validate the accuracy and precision of portable sleep monitoring devices through comparison with standard methods showing a very high rate of accuracy (Abrahamyan *et al.*, 2018). The general overview of portable sleep monitoring devices, their technical capabilities and potential applications were reviewed in several studied in detail (Kwon *et al.*, 2021; Guillodo *et al.*, 2020; Kelly *et al.*, 2012; Abrahamyan *et al.*, 2018). Table 1 summarizes a list of home sleep monitoring devices that have been employed to monitor sleep patterns during pregnancy. Figure 1 provides a detailed illustration of PSG setup with the existing cabling (left) and wearable portable sleep monitoring sensors (right) for a representative pregnant woman.

Application of home sleep monitoring devices to screen SDB in pregnancy

In parallel to the progress in portable monitoring technology, the utilization of ambulatory home sleep screening devices in pregnant population has also been steadily increasing. The application of home sleep monitoring devices to screen SDB in pregnant women is listed in Table 2. In a validation study on 31 pregnant women, O'Brein et al reported that the portable sleep monitoring device (Watch-PAT, Itamar, Cesarea, Israel) demonstrated high rate of sensitivity and specificity and positive and negative predictive values for identification of OSA in third trimester of pregnancy (O'Brien *et al.*, 2012b). They have reported that the performance of the Watch-PAT suggests that it could be used to facilitate simple and rapid screens of pregnant women, reduce waiting time for diagnosis. The same portable monitoring device were employed to diagnose OSA on 114 pregnant women in a comparison study with Berlin and ESS sleep questionnaires (Facco *et al.*, 2012). They have reported that the predictive values of the questionnaires were poor in screening OSA in high risk pregnant women. They have alternatively suggested a four-variable prediction rule including the presence of frequent snoring, chronic hypertension, age and BMI. They have reported that the proposed method more accurately predicts sleep apnea in pregnancy. However, Dominguez et al reported that this four-variable prediction rule is not useful in detecting OSA in a cohort of obese pregnant women (Dominguez *et al.*, 2018). They have evaluated established OSA screening tools including a sleepiness scale and type III home sleep apnea monitoring device (ApneaLink Air, Resmed, Poway, CA) on 80 pregnant women between 24 and 35-week gestation, with a body mass index ≥ 40 kg/m^2. They found that 24% of pregnant women have OSA defined as AHI ≥ 5 events per hour. Consequently, they have reported that the Berlin

Questionnaire, American society of Anesthesiologists checklist, STOP-BANG and the Epworth Sleepiness Scale were not useful tools for OSA screening in a cohort of obese pregnant women.

Facco et al used the Watch-PAT 100 home sleep monitoring device to study the prevalence and incidence of SDB in 128 high risk pregnant women (Facco *et al.*, 2014a). They reported 21% mild, 6% moderate and 3% severe SDB in early pregnancy whereas the frequencies increased to 35% mild, 7% moderate and 5% severe SBD in the third trimester. They also found that 27% of the women experiences a worsening of SDB during pregnancy and 20% were experienced new-onset SDB. Tantrakul et al used the same portable sleep monitoring device to evaluate the Berlin and Stop-Bang questionnaires in detecting OSA across trimesters of pregnancy in 72 pregnant women (Tantrakul *et al.*, 2015). They reported that while the questionnaires were of limited usefulness in the first trimester, their predictive power increases for the remaining period of pregnancy. They also reported that as a result of multivariate analyses, pre-pregnancy BMI in the first trimester, snoring frequency in the second trimester, weight gain in the third trimester were highly correlated with OSA. One important outcome of this study was that they reported the current screening questionnaires for OSA were originally developed for non-pregnant population. However, during the pregnancy there is a continuous change of physiology associated with OSA. Therefore, during the dynamic process of pregnancy, each trimester heavily correlates with different predictors.

In a study on 16 pregnant women, Sharkey et al assessed the validity of using a portable sleep monitoring device (Apnea Risk Evaluation System-ARES, Advanced Brain Monitoring, Inc., Carlsbad CA) for detecting OSA in pregnant women (Sharkey *et al.*, 2014). They have reported that the ARES device demonstrated reasonable consistency with PSG for diagnosing OSA. They have proposed the utilization of out-of-center testing to improve access and cut cost of evaluation for SDB particularly for pregnant women preferring home testing rather than stay overnight in the sleep laboratory.

Sarberg et al used a portable home sleep monitoring system (Natus Europe GmbH, Planegg, Germany) on 100 pregnant women to examine the difference in the prevalence of OSA and sleepiness between pregnant and non-pregnant women (Sarberg *et al.*, 2016). They have found that respiratory parameters including snoring showed no impact on obstetric outcomes and there was no increased prevalence of OSA among pregnant women. They provided as a potential reason of unchanged OSA prevalence could be that the majority of the women participated in the study was non-obese. Farabi et al (Farabi *et al.*, 2019) explored the correlation between the OSA in pregnant women with obesity and glycemic patterns on 18 pregnant women with BMI 30 to 40

kg/m^2. They reported that 12 of 18 women (67%) had an AHI ≥5 stating that mild OSA is common in pregnant women with obesity and correlated with increased glycemic profiles.

To estimate the predictive ability of OSA screening tools in pregnant women, Lockhart et al applied a home sleep monitoring device recording respiratory pressure, pulse rate, oxygen saturation and nasal cannula with no oxygen flow on 293 third trimester patients (Lockhart *et al.*, 2015). They reported that based on home sleep monitoring, none of the Berlin Questionnaire screening tools accurately detected OSA. They proposed a new screening tool based on promising components of different screening tools that may more accurately detect patients with OSA. From this point of view, the finding of this work lies highly in parallel with the outcome of Tantrakul et al (Tantrakul *et al.*, 2015).

Home sleep monitoring to estimate adverse maternal and fetal outcomes

In the context of maternal outcomes, hypertensive disorders, gestational diabetes, preeclampsia, caesarean delivery and maternal morbidity were considered. Fetal outcomes include preterm birth, low birth weight, small for gestational age and fetal heart rate responses. The application of home sleep monitoring devices to estimate adverse maternal and fetal outcomes is listed in Table 3.

Despite the growing evidence and increasing literature to link SDB in pregnancy with adverse maternal and fetal outcomes, the findings of studies with home sleep monitoring devices are conflicting similar to questionnaire and PSG based studies. In a prospective observational study on 175 women using an in-home portable PSG device (ARES), Loius et al reported that OSA prevalence was 15.4 % (Louis *et al.*, 2012). Compared to no OSA, the OSA group showed more chronic hypertension (55.6%vs 32.4%), more frequent caesarean delivery (65.4% v 32.8%) and preeclampsia (42,3% vs 16.9%) and neonatal intensive care unit admission (46.1% vs 17.8). They have reported that among obese pregnant women, OSA is associated more frequent preeclampsia, neonatal intensive care unit admissions and cesarean delivery. In contrary to the result of this work, in a later prospective cohort study on 188 women with a valid early pregnancy, Facco et al used portable sleep monitoring device (Watch-PAT100) to examine the relationship between SDB and adverse pregnancy outcomes (Facco *et al.*, 2014b). They reported that there was no relationship demonstrated between SDB exposure in early or late pregnancy and preeclampsia, preterm birth, small for gestational age whereas there is a dose-dependent relationship between SDB and gestational diabetes. Sanapo et al (Sanapo *et al.*, 2022) examined the association between maternal SDB and glucose metabolism in early gestation on 192

pregnant women with median BMI of 35.14 kg/m^2 using an in-home level III recording device, Nox T3 (Carefusion, San Diego, CA, USA). They have reported that a dose dependent association in early pregnancy between maternal sleep disordered severity and insulin resistance which is a precursor for gestational diabetes.

Yinon et al used the same portable sleep monitoring device on 17 females with preeclamptic toxaemia (PET) and 25 matched females with uncomplicated pregnancy by hypothesizing that females with PET may be associated both SDB and endothelial dysfunction (Yinon *et al.*, 2006). The have reported that both SDB and endothelial dysfunction are more likely to occur in females with uncomplicated pregnancies. Facco et al studied the preeclampsia and SDB to determine the prevalence of SDB among women with preeclampsia compared to normotensive controls using (Watch-PAT100) portable sleep monitoring device (Facco *et al.*, 2013). They have reported that preeclamptic subjects (20 preeclamptic patients) experience more SDB events and higher degree of nocturnal hypoxemia compared to normotensive controls (20 normotensive control patients). Ryu et al (Ryu *et al.*, 2023) studied the prevalence of OSA in 51 pregnant Korean women with BMI > 23 kg/m2 in gestational age of 30 weeks or more using WatchPAT. They reported that OSA is an important risk factor for preeclampsia resulting in preterm delivery in overweight pregnant women.

Pamidi et al used an in-home PSG device (Titanium, Embla, Natus Medical, San Carlos, California, USA) on 234 pregnant women to study the relationship between third trimester SDB and delivery of small for gestational age (Pamidi *et al.*, 2014). They have found that the symptoms of SDB in third trimester showed a potential association with delivering an SGA infant without reaching statistically significance, the home PSG based diagnosis of maternal SDB were significantly associated with the delivery of SGA infants. They reported that the use of routine ambulatory studies which largely depend on oxygen saturation events rather than arousals may provide false results in detecting the SDB in pregnancy.

In a prospective cohort study, Fung et al aimed to determine on 41 pregnant women in third trimester whether OSA is associated with reduced fetal growth and whether nocturnal oxygen desaturation precipitates acute fetal heart rate changes (Fung *et al.*, 2013). They found that the presence of objectively confirmed OSA in pregnancy can be associated with an adverse impact on fetal growth. They reported that OSA may be associated with reduced fetal growth in late pregnancy.

O'Brein et al studied the typical sleep positions in pregnant women to determine the proportion of pregnant women who sleep in the supine position. They deployed a portable monitoring device on 51 pregnant women (Medipalm, Braebon, Ontario, Canada or Embletta Gold, Embla Bromfield, CO) including the body position sensors differentiated 5 positions such as supine, right lateral, left lateral, prone and upright position. They reported that 82.4% of the pregnant women sleep at supine position which might play a role in stillbirth. Lucchini et al studied the effect of maternal sleep position on fetal and maternal heart rate on 42 pregnant women using a home monitoring device (Emblatta, Flaga Medical Devices, Reykjavik, Iceland) associated with the Monica AN24 fetal ECG monitor (Monica Healthcare System, Nottingham, UK). They have reported that maternal sleep position significantly affected maternal heart rate with left side sleeping associated with lower heart rate. Warland et al deployed Watch-PAT home sleep monitoring device to test whether a positional therapy would reduce the time spent sleeping supine positon with an effect on maternal and fetal parameters (Warland *et al.*, 2018). They have provided preliminary evidence that an intervention to reduce supine sleep in late pregnancy may confer maternal and fetal health benefits during late pregnancy. The work indicates that more SDB symptoms and decreased fetal heart rate are more common when the mother is sleeping in the supine position most probably as a result of the adaptive response of the fetus.

DISCUSSION

Emerging evidence now suggests that approximately one-third of pregnant women may be at risk for SDB which is likely associated with adverse pregnancy outcomes (Bourjeily *et al.*, 2011; Izci Balserak, 2015). Particularly during the third trimester of pregnancy, the prevalence of the main symptoms of SDB including habitual snoring and OSA is significantly increased relative to non-pregnant women. However, it is not a common practice among obstetricians to routinely screen the pregnant women for SDB (Bourjeily *et al.*, 2012). This is mainly because PSG which is currently the gold standard for screening is logistically not feasible and not practical to perform on all pregnant women at high risk for SDB due to the aforementioned reasons. Recent advances in mobile recording devices and wearable electronics suggest an alternative platform for home-based sleep monitoring to overcome the current challenges with PSG (Kelly *et al.*, 2012; Guillodo *et al.*, 2020; Kwon *et al.*, 2021) . Several work previously reviewed the polysomnographic features of pregnancy (Garbazza *et al.*, 2020). Same effort has not yet been performed for portable sleep monitoring devices although their application in pregnant women has been gradually increasing. To our best knowledge, this is the first study that provides an overview on the application of home

sleep monitoring devices in pregnant women and their efficiency in screening for SDB and estimating the perinatal outcomes.

Sleep questionnaires such as Berlin Questionnaire and ESS that provide subjective data to screen for SDB in pregnant women (particularly in obese pregnant women) must be carefully interpreted because of their low sensitivity and specificity compared to objective metrics provided by portable sleep monitoring devices. This is also confirmed by previous PSG based studies reporting that the questionnaires are not accurate tools to provide definitive and conclusive results in pregnant women (Olivarez *et al.*, 2010). This proposes that the establishment and verification of specific questionnaires particularly targeting the pregnant women are recommended to be utilized as a screening tool for SDB in pregnancy.

The home based sleep monitoring studies exploring the prevalence of SDB in at-risk pregnant women were commonly reported a significant degradation in the respiratory features during the pregnancy such as AHI, snoring frequency and oxygen desaturation index, especially in the third trimester (Facco *et al.*, 2012). Both the BMI in the range of obesity before the pregnancy and pregnancy triggered weight gain were found to be potential risk factors for the existing of OSA in pregnancy particularly at higher gestational age (O'Brien *et al.*, 2012a; Facco *et al.*, 2014a). Although these findings are in parallel with the previous PSG-based studies for women at-risk, there is not a conclusive evidence suggesting a major pregnancy induced deterioration in healthy and normal weight pregnant women (Garbazza *et al.*, 2020). Furthermore, among the non-obese women population, pregnancy does not alter the prevalence of OSA compared to non-pregnant women. However, in the obese women population, pregnancy increase the prevalence of mild OSA with apnea/hypopnea index (AHI) ≥5. This is also a common finding of the studies performed either by home sleep monitoring devices or PSG (Guilleminault *et al.*, 2000). Therefore, simple home-based sleep monitoring systems with high accuracy rate facilitating easy screening and detection of SDB are even more prominent for high BMI or obese pregnant women. Future studies should also investigate how appropriate to apply the existing criteria to diagnose OSA in pregnancy and may potentially define new metrics that better define the pathological thresholds in pregnant women. This requires large datasets and portable sleep monitoring systems can potentially be deployed in acquiring such big data.

Home sleep monitoring data regarding the association between SDB and adverse pregnancy outcomes are limited and not consistent. In some studies (Louis *et al.*, 2012), it has been reported that SDB increases the frequency of caesarean delivery and chronic hypertension and delivery of small for gestational age while one work reported that they found no relationship between SDB

exposure such perinatal outcomes (Facco *et al.*, 2014b). A few studies examined the association between SDB and preeclampsia reporting that SDB is an important risk factor for preeclampsia that may significantly influence the perinatal outcomes such as preterm delivery (Yinon *et al.*, 2006; Facco *et al.*, 2013; Ryu *et al.*, 2023). However, obesity seems, once again, plays a critical role in defining the association between SDB and maternal and fetal outcomes. Even the PSG based monitoring data that explore the link between SDB and severe perinatal outcomes are scarce, it has been reported that PSG-based diagnosis of SDB was significantly associated with delivery of small for gestational age (Pamidi *et al.*, 2014; Pamidi *et al.*, 2016). Another PSG based work reported that women with preeclampsia had inspiratory flow limitation and increased number of oxygen desaturation during sleep implying that preeclampsia is associated with reduced total fetal movements overnight (Blyton *et al.*, 2013).

Home sleep monitoring devices have not been applied yet to study some of the sleep-related aspects that were previously explored by using PSG in pregnant women. One major aspect is the change in sleep structure during pregnancy. According to the PSG-based monitoring, total sleep time is reduced in pregnancy because of the wake after sleep onset and there is a transition from REM sleep to NREM sleep stages particularly in the third trimester (Hertz *et al.*, 1992; Rimpila *et al.*, 2017). Even some portable sleep monitoring devices were recently used to stage sleep, there has been no data presented yet in pregnant women. Note that the changes in sleep structure in pregnancy might have a role on the consistency of the results obtained with portable monitoring systems compared to subjective questionnaires. Another unexamined aspect using home sleep monitoring devices is the frequency and characteristics of periodic leg movements during sleep (PLMS). This is may be because even the PSG-based studies did not show a relevant increase of PLMS-index in pregnant women (Dzaja *et al.*, 2009). According to our search, there is no result or data available that compares the sleep dynamics before and after delivery among those work performed with home based sleep monitoring systems.

Limitations

Limitations of the presented review should be considered to better understand some of the conflicting results among different studies. This analysis mainly reflects the broad spectrum of application of the portable sleep monitoring devices in pregnancy. The heterogeneity among the main characteristics of the analyzed studies including the population, study design, sample size, time of pregnancy and technical specs of data acquisition and recording limits to provide definitive conclusions. Second, there are no specific guidelines established for diagnostic evaluation of SDB in pregnant women. Standard procedures existing for the non-pregnant women are applied to

pregnant women to evaluate SDB which limits the clinical assessment of the findings. Third, the studies using portable sleep monitoring devices without having key recording channels for SDB screening (i.e. airflow) were excluded from the analysis. Finally, the rapid evolution and advancement in wearable electronics and sensor technology makes it difficult to keep up with all commercial monitoring systems. The limited reliability of the home based sleep monitoring systems may cause conflicting results in pregnancy. It is needed to provide non-invasive solutions and maintain the same level of accuracy and reliability as the clinical solutions. To improve the potential use of portable sleep monitoring devices in pregnancy and improve the reliability, it might be helpful to sample the pregnancy time of an individual patient such as first, second and third trimester and assess the alterations in sleep variables in different stages of pregnancy. Moreover, a consensus must be established for validating the accuracy of portable sleep monitoring devices and minimum standards must be defined on the accuracy criteria. Finally, publicly available datasets are highly important in assessing the accuracy and reliability of a system. There is a lack of publicly available datasets acquired from pregnant women. To improve the accuracy and reliability, large datasets must be created with portable sleep monitoring devices from pregnant women.

The advantages and disadvantages of home based sleep monitoring systems compared to PSG in general are equally valid for pregnant women. Portable sleep monitoring systems can facilitate simple screening of pregnant women, reduce waiting time and cost and provide large datasets with multiple-night recordings in the home environment to study the impact of SDB on fetal and maternal outcomes of pregnancy. However, home based sleep monitoring data are insufficient on the validity and reliability in the pregnant population.

CONCLUSION

Recent advancements in novel functional materials, new sensing structures, wearable electronics and advanced data analysis and processing methods (i.e. machine learning) enabled home based sleep monitoring to become an active research area. In this work, we have presented a comprehensive review of the recent research in the application of portable sleep monitoring devices in pregnant women. A growing number of home based sleep monitoring studies provide to collect large-scale data defining objective metrics of sleep parameters in pregnant women beyond subjective questionnaires.

Conflicts of interest

The authors have no conflicts of interest to disclose.

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FIGURE CAPTIONS

Figure 1. Comparison of the existing PSG setup and portable sleep monitoring devices for sleep monitoring A) The conventional PSG setting that requires multiple wired sensors and transducers to monitor sleep in a laboratory environment B) Portable device with wearable sensors and electronic systems to monitor sleep at home.

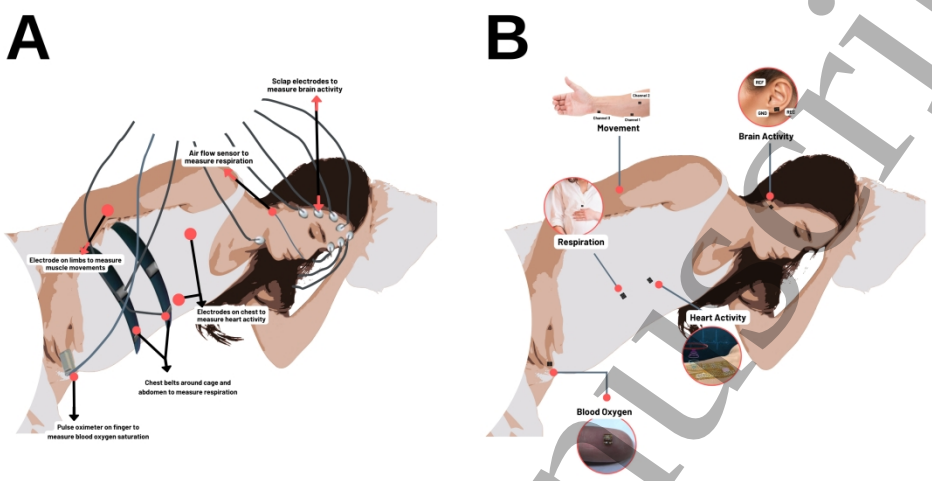

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Table 1. Literature review: The list of home sleep monitoring devices applied to monitor sleep patterns during pregnancy.

Device	Provider	Recording channels	References
Watch-Pat-100 Watch-Pat-200	Itamar Medical Cesarea, Israel	EEG, EOG, EMG, LEMG, ECG, nasal and oral airflow, chest and abdominal respiratory movement, SpO_2, snoring microphone, body position, PAT	O'Brein 2012, Facco 2012, Facco 2014, Tantrakul 2015, Farabi 2019, Facco 2014, Yinon 2006, Facco 2013, Ryu 2023, Warland 2018
Type III home sleep apnea test	ApneaLink Air; ResMed, Poway,CA	SpO_2, heart rate, respiratory effort belt, nasal airflow, snoring	Dominguez 2018,
ARES Unicoder	Advanced Brain Monitoring, Inc., Carlsbad,CA	SpO_2, pulse rate, head movement, head position, nasal airflow, snoring microphone	Sharkey 2014, Louis 2012,
Embla portable diagnostic system	Natus Europe GmbH, Planegg, Germany	Nasal airflow, abdominal and thoracic respiratory movements, body position and movement, SpO_2, heart rate	Sarberg 2016, Pamidi 2016, O'Brein 2014, Lucchini
Nox T3 level III recording device	Carefusion, San Diego,Ca, USA	Nasal pressure, audio recording, body position and movement, ECG, SpO_2, chest and abdominal respiratory movement,	Sanapo 2021,
Somte PSG portable sleep monitoring device	Compumedics, Abbotsford, Australia	EEG, EOG, nasal airflow, SpO_2, chest and abdominal respiratory movement, heart rate, body position	Fung 2013

Table 2. Literature review: The application of home sleep monitoring devices to screen SDB in pregnant women

Author	Year	Patients	Study Design/Methods	Results/Conclusion
O'Brien	2012	31 pregnant women	Prospective cohort study, full overnight portable PSG and Watch-PAT 200 device	Evaluation for SDB during pregnancy must be prioritized. Moderate to good (r=0.68-0.94) correlation of the parameters of PSG and Watch-PAT. Useful for rapid screening of pregnant women in addition to making sleep research more feasible in this population
Facco	2012	114 pregnant women	Prospective study comparing the performance of Berlin Questionnaire and Epworth Sleepiness Scale (ESS) with WP100 device in detecting sleep apnea	The Berlin and ESS are not reliable predictors of sleep apnea in high-risk pregnant women. A four variable screening based on self-reported snoring, chronic hypertension, BMI and age more accurately predicts sleep apnea in pregnancy
Dominguez	2018	80 pregnant women between 24 and 35 weeks gestation	Prospective study to evaluate established OSA screening tools, a sleepiness scale, and individual component items in a cohort of pregnant women.	The Berlin Questionnaire, American Society of Anesthesiologist checklist, STOP-BANG, OSA in pregnancy score by Facco et al and Epworth Sleepiness Scale were not useful screening tools for OSA in a cohort of obese pregnant women.
Facco	2014	128 pregnant women	Prospective study to determine the prevalence and incidence of SDB in pregnancy among high-risk women using WP100 device	SDB in early pregnancy is common in high-risk women and new-onset SDB occurs in 20% of these women. New-onset SDB during pregnancy is more common in twin pregnancies
Tantrakul	2015	72 singleton pregnant women	Prospective study to assess Berlin and Stop-Bang questionnaires in detecting OSA across trimesters with WP200 device	Screening questionnaires in high-risk pregnancy are poorly predictive of OSA during the first trimester. The most appropriate time to use Berlin and Stop-Bang questionnaires is during the second and third trimester
Sharkey	2014	16 pregnant women	Comparison study to validate an ambulatory apnea monitoring device with PSG in pregnant women to detect OSA	The ARES unicorder device demonstrated reasonable consistency with PSG for diagnosing OSA in the sample of obese pregnant women
Sarberg	2016	100 pregnant women	Prospective study to examine if there is a difference in the prevalence of OSA and sleepiness in pregnancy monitored by an ambulatory PSG device	There was no increased prevalence of obstructive sleep apnea among pregnant women. Neither OSA nor snoring was likely an explanation for the increased daytime sleepiness seen in the pregnant women
Farabi	2019	18 pregnant women with BMI 30 to 40 kg/m^2	Prospective study to explore the link between OSA and altered glycaemic patterns in pregnant women with obesity	Mild OSA is common in pregnant women with obesity and correlated with increased glycemic profiles.
Lockhart	2015	293 third-trimester patients	Prospective study to estimate the predictive ability of current OSA screening tools.	Compared to the home sleep monitoring, none of the OSA screening tools based on Berlin questionnaire accurately detected OSA in pregnant women in the third trimester.

Table 3. Literature review: The application of home sleep monitoring devices to estimate adverse maternal and fetal outcomes

Author	Year	Patients	Study Design/Methods	Results/Conclusion
Loius	2012	175 pregnant women	Prospective study to screen OSA among obese pregnant women. Perinatal outcomes were compared between women with and without OSA	OSA prevelance was 15.4% among 175 women. OSA was associated with more frequent ceserean delivery (65.4% compared with 32.8%), preeclampsia (42.3% compared with 16.9%) neonatal intensive care unit admission (46.1% compared with 17.8%)
Facco	2014	188 pregnant women	Prospective cohort study to estimate the prevalence and trends of SDB in high risk pregnant women using WP100	A dose-dependent relationship between SDB in early pregnancy and the subsequent development of the gestational diabetes. In contrast, no relationships between SDB during pregnancy and preeclampsia, preterm birth and extremes of birthweight were observed
Sanapo	2022	192 pregnant women with median BMI of 35.14 kg/m^2	Observational study to examine the association between maternal sleep disordered breathing (SDB) and glucose metabolism in early gestation.	SDB and insulin resistance are associated in early pregnancy with a dose response association between respiratory event index severity and insulin resistance.
Yinon	2006	43 pregnant women	Case-control study to examine the association of Pre-eclampsia with sleep disordered breathing and endothelial dysfunction using WP100	Both sleep-disordered breathing and endothelial dysfunction are more likely to occur in females with pre-eclamptic toxaemia than in females with uncomplicated pregnancies
Facco	2013	20 preeclaptic and 20 control women	Case control study to determine whether SDB is more prevalent among women with preeclampsia than among normotensive controls using WP100	Compared to normotensive controls, preeclamptic subjects experience more SDB events and a greater degree of nocturnal hypoxemia
Ryu	2023	51 pregnant women with BMI > 23 kg/m^2 in gestational age of 30 weeks or more	Prospective study to examine the prevalence of OSA and to assess the impact of OSA on pregnancy related disorders in overweight pregnant women.	OSA is an important risk factor for preeclampsia resulting in preterm delivery in overweight pregnant women.
Pamidi	2016	234 pregnant women	Prospective cohort study to assess the link between PSG based diagnosis SDB with the delivery of small for gestational age (SGA) infants	An increased risk of delivering small for gestational age infants with maternal sleep-disordered breathing was reported
Fung	2013	41 pregnant women	Prospective study to determine whether OSA is associated with reduced fetal growth using laboratory and ambulant PSG	OSA may be reduced with fetal growth in late pregnancy
O'brein	2014	51 third-trimester pregnant women	A secondary analysis to determine the proportion of pregnant women who spend time asleep in the supine position.	The vast majority (82.4%) of the pregnant women spend time asleep on their back.
Lucchini	2020	42 third-trimester pregnant women	Observational study to assess the effects of maternal position on maternal and fetal heart rate and heart rate variability.	Maternal position affected maternal heart rate with left side sleeping associated with lower heart rate (left vs right P=0.017, left vs supine P=0.027) and higher overall heart rate variability (left vs right p=0.032).
Warland	2018	25 healthy pregnant women	Prospective study to test whether a customized positional therapy device would reduce time spent sleeping supine and evaluate any change in maternal or fetal parameters	The work indicates that more SDB symptoms and decreased fetal heart rate are more common when the mother is sleeping supine most probably as a result of the adaptive response of the fetus.