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CLINICAL REVIEW

Is sleep education an effective tool for sleep improvement and minimizing metabolic disturbance and obesity in adolescents?

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S U M M A R Y

The prevalence of childhood obesity has increased significantly in recent years. Obesity is associated with a range of adverse physiological, psychological and social outcomes and places a huge economical burden on healthcare systems around the world. Insufficient sleep duration is common in adolescents and exacerbated by contemporary lifestyles, but may be a contributor to obesity onset and metabolic disruption. We briefly review the current evidence surrounding the associations between sleep and obesity as well as diabetes. Sleep improvement programs have been suggested as a potential avenue to raise awareness of the importance of sleep and ultimately enhance sleep behaviors/routines. A review of the current literature supporting the efficacy of such programs is tentative. Furthermore, very few studies have investigated if sleep enhancement has downstream positive effects on metabolic function or body weight in adolescents. We highlight biological and social factors that intensify sleep loss in adolescents and recommend that these be targeted components in future interventions aimed at improving adolescent sleep.

Introduction

The global economic burden of obesity is estimated at $2 trillion, accounting for almost 3% of total healthcare costs [1]. The rising prevalence of obesity and type 2 diabetes mellitus in pediatric populations are of particular concern [2]. The World Health Organization (WHO) estimates that there are 42 million overweight children under the age of 5 y [3]. Previously, type 2 diabetes diagnoses were confined to older age groups, but type 2 diabetes is now increasingly observed in pediatric populations [2]. Persistence of pediatric overweight/obesity into adulthood has been observed [4]. Whilst there is a complex genetic contribution to metabolic disease [5], lifestyle behaviors have driven the rising prevalence of obesity and diabetes and have been the main target for interventions aiming at minimizing these conditions [6–8]. It is well established that positive energy balance (excessive energy intake and insufficient energy expenditure) is a major contributor to diabetes and obesity [5]. Sleep has, however, emerged as a tertiary lifestyle factor. Educating individuals about the importance of sleep has been suggested [9–12], particularly as a potential avenue to address adolescent obesity [13,14]. There is some literature available regarding the efficacy of sleep improvement programs and the potential influence upon addressing obesity and metabolic regulation, which is the primary focus of this review.

Sleep is a complex phenomenon that is regulated by two mechanisms named process S (homeostatic drive) and process C (circadian drive) [15]. The homeostatic drive is appetitive with sleep drive increasing with greater wakefulness. The accumulated sleep debt, developed during the day, is paid off during sleep, when the homeostatic drive is maximal. The circadian drive determines timing of sleep ensuring wakefulness in the evening, where the homeostatic drive signals the need for sleep, and in the morning on awakening to support alertness. In adolescence, sleep-

Abbreviations: BMI, body mass index; PSQI, Pittsburgh sleep quality index; SE, sleep efficiency; SOL, sleep onset latency; SWS, slow wave sleep; TIB, time in bed; TST, total sleep time.

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wake patterns are shifted and delays in sleep initiation and wakefulness are driven by multiple intrinsic and extrinsic factors (see Table 2). Extreme misalignment of process C has been simulated under laboratory conditions in at least two small studies of young adults [16,17]. Both studies highlighted adverse metabolic outcomes that could contribute to the onset of obesity [17] and type 2 diabetes [16]. Whilst the shift in process C, commonly observed in developing adolescents, is less extreme compared to that simulated in the studies described, a small but chronic shift in process C may have meaningful cardio-metabolic consequences. Recent longitudinal data have confirmed that persistent later bedtimes across adolescence are linked to subsequent increases in body mass index (BMI) and an increased risk of obesity [18]. Interventions to minimize delays to process C and realignment of the two processes involved in sleep can improve this behavior in adolescents.

In this review, we briefly outline the evidence surrounding the relationship between sleep parameters (sleep duration, sleep quality [sleep efficiency], and sleep architecture, specifically slow wave sleep [SWS]) and metabolic health outcomes with mechanistic explanations. We then discuss the preliminary evidence relating to the efficacy of sleep education programs, for improving sleep duration as a potential avenue to address metabolic health and disease. Finally, we discuss limitations of the existing studies and provide recommendations for future research when considering the development, design and application of such programs for delivery to adolescent populations. We highlight the importance of intrinsic and extrinsic drivers of sleep loss in adolescence, and suggest these to be key targets in future interventions aimed at improving sleep and ultimately metabolic health in this vulnerable age group.

Evidence of a sleep-obesity association in pediatrics

Obesity is a complex disease arising from multiple direct and indirect factors (see Fig. 1). Adolescents are susceptible to developing obesity and are vulnerable to its effects [19]. Many adolescents fail to achieve sufficient sleep quantity [10,11] and this, as well as poor sleep quality and late circadian preference has been linked to a plethora of adverse health outcomes and metabolic disruption [9,20–22]. Two early epidemiological studies reported a sleep-obesity relationship in children [23,24]. Whilst these studies highlighted an important novel relationship between sleep and obesity, which indicated sleep as a fundamental behavior for pediatric health, weaknesses of these, and similar studies, include: 1) use of parental report for sleep duration, which may be inaccurate [25]; 2) use of BMI to determine excess adiposity, which may be problematic, particularly in children where physical development occurs on a wide spectrum and is confounded by children entering puberty at younger ages than before [26]; 3) lack of examination of temporal associations from cross-sectional study designs [23,24]; and 4) study design for purposes other than examining the role of sleep in health. Some of these drawbacks have now been addressed [9,27,28] and have provided further evidence to support a link between sleep loss and obesity in pediatric populations. Furthermore, meta-analyses have shown that insufficient sleep in pediatrics is associated with an increased risk of obesity, ranging from 58% to 89% [29,30].

Sleep and diabetes in pediatrics

Obesity is closely linked to insulin resistance and type 2 diabetes, an increasingly common condition in pediatric populations [2]. The relationship between sleep and type 2 diabetes has previously been investigated [31–33]. Sleep architecture has been assessed in 118 children (mean age 13.1 ± 3.3 y) using polysomnography [32]. Those with greater sleep efficiency (percentage of time spent sleeping of the total amount of time spent in bed) and longer sleep duration had significantly lower 2-hour glucose levels, after adjustment. Insulin sensitivity was greater in those with more SWS, where $\beta = 0.024$, $p = 0.012$ and in those with better sleep efficiency $\beta = 0.013$, $p = 0.016$ [32]. Other groups have reported similar findings for SWS and insulin resistance/secretion in various populations (healthy weight, overweight, and obese) [31,33].

Mechanisms involved in sleep and metabolic health

The suprachiasmatic nucleus regulates sleep-wake timings and disruption to these patterns, whether in an experimental setting or undertaken voluntarily in the natural environment, may influence biological oscillations of the appetite-regulating hormones and feeding behaviors. In particular, leptin levels in healthy adults peak during sleep (between 22:00 and 03:00 h) and are lower during the day (08:00–17:00 h) [34]. Conversely, ghrelin levels are lower during sleep, peaking pre-prandially and decrease after energy intake [35].

Disruption to these hormones occurring from experimental sleep loss have been linked to an increased appetite for energy-dense foods in adults [20]. Whilst Beebe and colleagues examined changes in food intake following experimental sleep reduction in adolescents, metabolic hormones were not assessed [36]. The authors applied a cross-over study design with experimental sleep restriction (6.5 h/night monitored by wrist actigraphy) in mid-adolescents (aged 14–16 y) and reported a significantly increased number of self-reported daily sweet/dessert portions, and foods with a higher glycemic load, compared to when adolescents were in the 'healthy' sleep condition (10 h) [36]. Further recent work by the same group, revealed consistent findings showing an elevation in calorie intake following sleep restriction [37].

Sleep loss has also been associated with reduced glucose tolerance (40% reduction in glucose clearance after an intravenous glucose tolerance test following sleep restriction [four hours for six nights] versus sleep recovery [12 h for six nights]) as well as significant elevations in evening cortisol levels in adults [38]. In the normal state, cortisol levels are lowest in the evening. Alterations in sleep, a predominantly brain phenomenon, impinge on peripheral hormones via the autonomic nervous system, regulated by the hypothalamus. Sleep deprivation results in over-activation of the sympathetic nervous system [38], purported to promote insulin resistance and obesity-driven metabolic syndrome [38,39].

Mechanistic studies examining neural responses of sleep reduction upon appetite in young adults have shown that specific brain regions, known for appetite regulation and food desirability, are also affected by sleep loss [40]. Alterations to these brain regions may mediate changes in desirability and selection of unhealthy food types [40]. In turn, these behaviors can promote weight gain and subsequent obesity particularly if sleep loss persists and becomes habitual.

Effectiveness of sleep improvement programs

A consistent negative linear relationship has been observed between sleep quantity and obesity in pediatrics [9,23,24,28], with supporting prospective [28,41–43] and meta-analytic evidence [29,30]. Inter-related factors surrounding sleep, obesity and metabolic disruption are now well understood, but the question now is, if delivery of sleep improvement programs is an effective tool for improving sleep and ultimately resolving obesity and/or improving metabolic health.

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Table 1
Adolescent sleep education programs identified from the literature search.

Authors (year)	Sample size	Country	Details of the intervention	Sleep measure	Main findings
Azevedo et al. (2008) [53]	25	Brazil	12 daily 50-min sessions over one-month	Questionnaire & diary	No significant change to TIB or sleep-wake times on weekdays or weekends
Bei et al. (2013) [48]	10 females	Australia	Six sessions of 90-min mindfulness techniques	Questionnaire & seven-day actigraphy	Improvements to objective SOL, SE (%), TST, earlier bed/wake times and reduced day-to-day bedtime variation. PSQI global score reduced post-intervention
Beijamini & Louzada 2011) [54]	10 (intervention) 11 (controls)	Brazil	Four 50-min education sessions	Actigraphy, questionnaire & diary	No significant change to any sleep parameter in either group
Cain et al. (2011) [55]	53 (intervention) 51 (controls)	Australia	Four 50-min education sessions (intervention only)	Questionnaire	Improvement in TST from baseline to post-intervention in both groups
de Sousa et al. (2007) [56]	58	Brazil	50-min daily sessions for one-week	Questionnaire & diary	No significant changes to sleep-wake times, TIB or sleep quality on weekdays or weekends
[a]Dewald-Kaufmann et al. (2013) [49]	28 (intervention) 27 (controls)	The Netherlands	Personalized sleep-wake schedule with 5-min advancing bedtimes & sleep hygiene for 2 wk (intervention only)	Diary & actigraphy	Intervention group advanced bedtimes, had earlier sleep onset, more TIB and greater TST compared to controls
[a]Dewald-Kaufmann et al. (2014) [50]	28 (intervention) 27 (controls)	The Netherlands	Personalized sleep-wake schedule with 5-min advancing bedtimes & sleep hygiene for 2 wk (intervention only)	Diary & actigraphy	Intervention group advanced bedtimes, had earlier sleep onset, more TIB and greater TST compared to controls
Kira et al. (2014) [51]	15 (intervention) 14 (controls)	New Zealand	Four 50-min education sessions (intervention only)	Questionnaire	Extended weekend sleep duration in the intervention group. No difference for weekday sleep duration
Moseley & Gradisar (2009) [57]	41 (intervention) 40 (controls)	Australia	Four 50-min education sessions over four weeks (intervention only)	Questionnaire	No significant sleep improvement
Sousa et al. (2013) [58]	18 (intervention) 16 (controls)	Brazil	Five 50-min education sessions over one-week	Questionnaire & diary	Weekdays: Significantly later wake up times (intervention) and greater TIB in both groups. Weekends: Significantly earlier bedtime (intervention) and earlier wake time (both groups). Sleep irregularity: significant improvement (intervention group)
Tan et al. (2012) [47]	33	New Zealand	Initial 90-min one-to-one session then additional one-to-one sessions every six weeks	Waist accelerometry & questionnaires	Improvement to sleep outcomes based on questionnaires although no significant differences for sleep duration was detected with accelerometry. BMI z-score significantly decreased post-intervention
Wing et al. (2015) [52]	1545 (intervention) 2168 (controls)	Hong Kong	One-hour seminar; two 40-min workshops with small group discussions; quizzes & a competition	Questionnaire	Sleep duration significantly reduced in the intervention and control group post-intervention

TIB = time in bed; TST = total sleep time; SOL = sleep onset latency; SE = sleep efficiency; PSQI = Pittsburgh sleep quality index.
[a] Data derived from the same sample.

Table 2
Some factors affecting sleep timing and duration in children and adolescents.

Factor	Impact on sleep duration and timing
Light	Light near bedtime delays sleep onset Darkness increases melatonin secretion that promotes sleep A dark bedroom encourages sleep onset Light near wake time enhances alertness
Caffeine	Caffeine near bedtime reduces sleep homeostatic drive and delays sleepiness
Temperature	A cool bedroom environment promotes sleep
Noise	Noisy environments and listening to music near bedtime affects sleep
Physical activity	Physical activity near bedtime delays sleep
Food intake	Eating a large meal near bedtime may interrupt sleep and/or delay sleep initiation
Nicotine and alcohol use	Use of these substances by adolescents has deleterious effects on sleep
Stress/mental health	The transition from childhood to adulthood results in many stressful events, including increased academic pressure, conflicting child-parent views; these encounters are likely to result in stress which can result in alterations to sleep
Peer/social influences	Adolescents exercise increased autonomy and may be influenced by peers (socializing late in the evening either through technology or in an external environment) which could lead to poor decisions about sleep timing
Perceptions/beliefs	Perceptions and beliefs about sleep are likely to be important and influence sleep behaviors although this is a largely overlooked area
Genetics/family environment	Genetics play a role in circadian preference and will influence sleep-wake timings, in line with parental sleep behaviors
Bedroom environment	Availability and engagement with technology in the bedroom reduces sleep duration, increases sleep latency and may promote some parasomnias

Recent retrospective evidence from 83 obese adolescents (without sleep advice) demonstrated enhanced weight loss (BMI) at three months in those with longer weekly self-reported sleep duration [14]. This suggests that optimal sleep could normalize energy balance, and may contribute to weight loss and perhaps improve metabolic function, such as insulin sensitivity.

Do sleep improvement programs work?

Given the increasing evidence for a role of short sleep on obesity and key metabolic parameters, it is important to examine the evidence for interventions aiming to improve sleep in younger populations. A systematic search was conducted to ascertain the impact of sleep improvement programs.

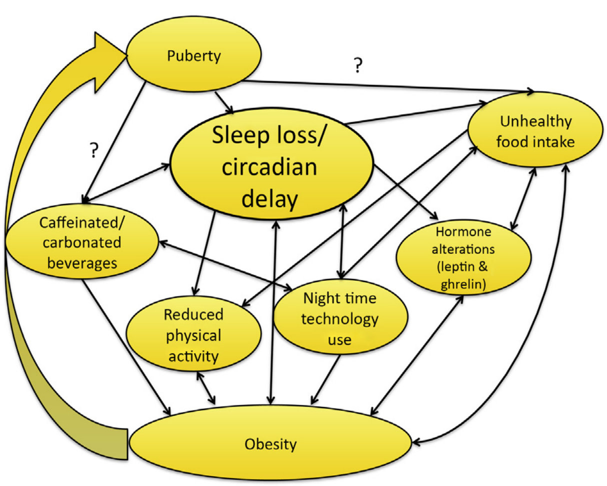

Fig. 1. Proposed pathways and interactions of the biological and social factors related to sleep loss and/or circadian delays that may contribute to obesity and metabolic disruption. Insufficient sleep or delayed sleep-wake patterns have been linked to increased body mass index (BMI). Increased BMI, in turn, has deleterious effects on sleep. Sleep loss/circadian delay has been associated with increased calorie consumption of unhealthy food types (snacking), possibly as a result of increased waking time/opportunity. A bi-directional relationship may exist between inadequate sleep/circadian delay and caffeinated/carbonated beverage intake as well as night-time technology use. Sleep loss/circadian shift has been associated with changes in appetite-regulating hormones and reduced energy expenditure. Puberty and increasing social interaction may be associated with changes in dietary behaviors such as increased consumption of caffeinated/carbonated beverages and unhealthy food selection. Puberty can also contribute to sleep loss and circadian delays and obesity has been related to earlier onset of puberty.

Methods

To identify articles relating to sleep improvement programs in adolescents, we searched the titles and abstracts of four electronic databases (PubMed, EMBASE, Web of Science and Scopus) using the terms: "sleep education", "sleep hygiene", "sleep improvement", "adolescen*", "teen*", "student*". Articles were included if the study included adolescents (aged 10–18 y), the full text could be accessed and was in English, if the article was published between 1980 and 2016, and if one or more sleep parameters were assessed before and after the intervention (subjective or objective). We also inspected previous reviews [44–46] in the topic area to ensure that relevant articles were not omitted. A total of 12 studies were identified and summaries for each can be found in Table 1.

Findings from sleep improvement programs

Given the multitude of factors known to influence sleep duration and quality (see Table 2), sleep improvement programs should be multi-faceted, with a specific emphasis on key factors that affect sleep. Whilst some have investigated the effects of sleep advice in those with poor sleep habits [47], raising awareness and educating adolescent populations about healthy sleep habits is unlikely to be harmful. That said, delivering an effective multi-faceted global sleep education program to adolescents requires further investigation prior to implementation. There have been a number of recent attempts to assess the efficacy of sleep education programs in adolescent populations [47–58], which will be discussed. However, changes in body weight and/or metabolic alterations have not been the primary outcomes of interest, with the exception of one study which measured BMI z-score pre- and post-intervention [47].

Two distinct sleep education intervention approaches have been used to date: 1) those intended to raise awareness and improve sleep knowledge only, and; 2) those intended to improve sleep outcomes. For the purpose of this review, we focus on the latter, specifically in adolescents. There has been a recent surge of sleep education programs in adolescents, although the evidence for improving sleep duration is inconsistent with some demonstrating improvements in those subjected to an intervention [48–50,58], others reporting no change [47,53,54,56,57], whilst others have noted improvements for weekend but not weekday sleep duration [51], yet some report a decline in sleep duration, post-intervention [52]. Furthermore, two studies reported enhanced sleep features in the intervention as well as the control group [55], suggesting that recruitment to a sleep program may modify behavior, even without intervention. Such discrepancies are likely to result from differing study designs, and small sample sizes where generalizability is an issue, inconsistent utilization of sleep duration measures, and differences in the content, intensity, length, mode of delivery and setting of the programs.

Wing and colleagues performed the largest study to date using a cluster randomized controlled trial, incorporating 14 Hong Kong high schools (six were randomized to the experimental group) and a total of 3713 adolescents (12–18 old; 40.2% male) [52]. The sleep education program was comprised of 1) a one-hour seminar delivered by experienced sleep physicians covering sleep importance, sleep deprivation consequences, contributing factors of sleep loss and good sleep practices; and 2) two 40-min small group (n = 30–40) workshops, held once per month, led by trained researchers initiating small group discussions and case studies. After the first workshop, participants were requested to complete a seven-day sleep diary for individual review. The program also taught stress-coping management techniques, distributed brochures, leaflets and developed a sleep educational website (provided to all participants, parents, and teachers). Participants in the experimental condition also entered a slogan competition to highlight the importance of sleep and good sleep practices (71.6% response rate). Parents and teachers were invited separately to a one-hour sleep seminar. Baseline data were ascertained three months prior to the intervention and follow up data were collected one-month post-intervention. The intervention was conducted over a four-month period. Benefits of this study included: 1) comprehensive sleep education program (regular sleep-wake schedule, avoiding stimulants and use light-emitting devices close to bedtime, regular exercise, stimulus-control and more); 2) randomized study design; and 3) the largest sample size to date. Limitations of the study included self-reported outcomes, no measures during the intervention to detect possible changes in sleep behaviors, and the effect of the complete intervention was examined rather than individual components. No significant alterations were observed for sleep duration post-intervention [52]. Whilst sleep education improves knowledge, this may not indicate behavior modification. Interestingly, some studies have shown it is possible to extend sleep duration (at least time in bed) upon instruction without detailed sleep advice, suggesting sleep extension is possible to achieve with minimal guidance [59].

Kira and colleagues developed and piloted a sleep improvement program to adolescents, aged 13–16 y [51]. Fifteen participants were randomized to the sleep intervention group and 14 to the control. All participants underwent baseline measures including completion of a battery of questionnaires (sleep and demographics) and a seven-day sleep diary. The intervention comprised of four 50-min sessions, presented by a health education teacher at the school, and the primary outcome of interest was alterations in sleep duration (derived from 7-d sleep diaries) at ten weeks post-intervention compared to baseline. Average weekend sleep duration was significantly enhanced by 1-hour and 19 min in the experimental group at 10 wk post-intervention ($p = 0.03$), which was partially explained by later waking times during weekends. Conversely, a 37-min reduction in mean weekend sleep duration was observed in controls [51]. A key component of sleep improvement is ensuring a consistent sleep-wake routine, across weekdays and weekends. Improvements to sleep duration are crucial, but lengthening weekend sleep duration may intensify weekday sleep loss and negative outcomes may ensue [60–63]. Thus, the program piloted by Kira and colleagues may be paradoxical [51], resulting in poor sleep habits and chronic weekday sleep loss. However, the findings from this study are tentative and subject to limitations including potential contamination bias, subjective sleep measures, and absenteeism at educational sessions with no replacements offered.

Cognitive behavioral theorists postulate that key criteria are required to achieve successful behavior change. These include 1) acknowledgment of the problem to be targeted (sleep insufficiency); and 2) motivation and belief in the ability to change the behavior (self-efficacy) [64,65]. One group applied these criteria and examined 55 adolescents (12–19 y) with self-reported sleep problems [49,50]. Participants randomized to the experimental condition were instructed to gradually extend sleep by advancing bedtimes by five minutes each night for two weeks and maintain a consistent sleep-wake pattern (simple sleep hygiene) whilst being monitored objectively by wrist actigraphy. There was evidence for extended sleep duration, albeit small (13 min), with significant improvements to cognition [49] and symptoms of depression [50].

Another group recruited 33 adolescents (10–18 y) with self-reported sleep problems, provided sleep advice, and monitored participants with waist accelerometry, multiple times before and after the sleep intervention to investigate the effects of the sleep intervention upon sleep duration [47]. Multiple self-reported sleep improvements were noted, although accelerometry-estimated sleep duration remained unaltered. Interestingly, despite no change in objective sleep duration, BMI z-score decreased post-intervention (0.66 ± 1.19) compared to baseline (0.79 ± 1.18), $p = 0.001$, as well as sedentary activity [47]. It is possible that other sleep improvements occurred, possibly resulting in increased physical activity levels with subsequent reductions in BMI.

Hart and colleagues recently assessed the impact of alterations to sleep duration upon energy intake, metabolic hormones and body weight [59]. Whilst this is the first pediatric study to examine the influence of sleep upon food intake, appetite-regulating hormones and body weight alteration, the study was conducted in a sample of 37 pre-adolescents, aged 8–11 y (57% male). Children were randomized to either one-week of 1.5 h increase/decrease time in bed, repeating the other condition the following week, aiming to achieve a 3-hour difference in sleep duration between conditions. Food recalls (24 h) were completed six times across the study period. Adherence to each sleep condition demonstrated an average difference of 1 h 46 min based on actigraphy-scored data. Following sleep extension, average body weight declined by 0.22 kg ($p < 0.001$), as did daily calorie intake (134 kcal per day, $p = 0.04$), compared to sleep restriction. Significant decreases in leptin (−18.6%, $p = 0.04$) were observed following sleep extension but no differences were found for ghrelin [59]. The study demonstrates that sleep duration can be extended and is associated with positive health-related outcomes. However, given that this study was conducted in pre-adolescents and involved parents, it may not be generalizable to adolescent populations. Furthermore, those initially assigned to sleep restriction may appear to demonstrate sleep extension in the subsequent condition as a result of accumulated sleep debt given that no washout period was applied between conditions. Finally, the method(s) used to achieve sleep extension was not explicitly described in this study.

Limitations of tested sleep interventions

The efficacy of sleep interventions, which have targeted adolescents, should be interpreted with caution. Between-study

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comparisons are difficult given that the content, setting, duration and samples are heterogeneous. The majority of the studies outlined have been performed in small sample sizes [47–51,53,54,58], thus generalizability to other adolescent populations is a current challenge. Some studies have used self-reported sleep measures, and whilst sleep diary data have been shown to agree with actigraphy estimated sleep duration, questionnaire data are less reliable [66]. Of the 12 studies included, seven reported some positive sleep behavior change post-intervention [47–51,55,58]. There are however, some considerations that need to be highlighted: 1) data duplication [49,50]; 2) no control group for purposes of comparison [48]; 3) sleep improvements noted for controls as well as intervention groups [55,58]; 4) enhanced weekend sleep duration but not weekday [51], which can widen the weekday-weekend sleep discrepancy, known to be important for metabolic health [67].

Alterations in appetite and metabolic regulation as well as obesity outcomes are limited in adolescent populations, with just one study examining the change in BMI z-score pre- and post-intervention [47]. There are some preliminary data from young, overweight adults, enrolled to a sleep extension intervention and monitored by actigraphy, that have shown a 14% reduction in overall appetite ($p = 0.03$) and a 62% decreased desire for unhealthy food types ($p = 0.02$) [68]. Additional support for the ability to achieve sleep extension with positive effects on feeding behavior, body weight and metabolic regulation in pre-adolescents is also available [59]. All of the studies have examined the possibility of extending sleep duration. However, sleep quality and architecture are also important for metabolic health in adolescence [32]. Furthermore, adolescent sleep-wake timings, which are influenced by circadian delay, have emerged as potential drivers of obesity in adolescence [9,18]. A more holistic approach to improve multiple aspects of sleep may therefore be required to target metabolic regulation and health in this age group.

Future directions

The success of programs aimed at improving sleep in adolescents is provisional. The exception to this, are techniques used which are underpinned by theories of behavior change. This includes a number of small studies that have shown the effectiveness of brief cognitive behavioral therapy to improve sleep and related behaviors/conditions in those with insomnia [69–71]. There are at least two potential explanations for this. Firstly, adolescents with greater sleep difficulties paired with additional problems (substance use, depression) may be more driven to change behavior given the downstream effects that sleep loss has on other aspects of their daily lives. Secondly, smaller groups or individual sessions, as opposed to delivering education to larger groups in a classroom setting may be required to optimize success. Furthermore, delivering an education program to large groups of adolescents may not be the best approach given that not all adolescents will experience sleep difficulties. Thus, sleep is unlikely to change in these individuals and may therefore minimize the efficacy of an otherwise successful intervention.

Several considerations for the delivery and efficacy of school-based sleep education programs have been highlighted in Blunden and Rigney's recent systematic review [44]. Firstly, many sleep improvement programs have not applied an evidence-based psychological theory of behavior change [44]. Secondly, the location/setting, content, intensity, duration and the individual that delivers the program are all important features [44,52,72]. Content should be influenced by prior knowledge (chronotherapy in relation to technology use [73–75], energy/caffeinated beverages [74,75], and dietary habits [9] are essential components) and should be underpinned by a well validated psychological theory of behavior change. In particular, social cognition models have demonstrated some of the most promising results for increasing physical activity in adolescents [76]. There is preliminary evidence for internet-based/group cognitive behavioral therapy to improve symptoms of insomnia in adolescents [69]. A 'one-size-fits-all' approach is unlikely to be successful across all groups and cultural beliefs/behaviors undoubtedly need to be accounted for during study development and design. Different aspects may contribute to sleep insufficiency in different individuals; therefore an holistic approach may not be beneficial. Thus, tailored interventions to improve adolescent sleep are now becoming more favorable [77]. However, identifying which specific aspects drive positive behavior change in tailored interventions is difficult to determine and reporting the precise details is challenging yet essential. Different ethnicities/cultures may require targeting different behaviors, such as napping [78]. Daytime napping may decrease sleep pressure (process S) and interfere with smooth alignment of the two-process model of sleep [15], previously described. A further example is timing of meals, which may be delayed in some cultures to ensure family focus [79]. Overcoming these issues requires comprehensive consideration, thought and consultation. Motivation to modify behavior, attitude, past behavior and self-efficacy have all been related to more favorable outcomes [80] and should be determined in future studies targeting behavior change.

Clinical trials targeting physical activity and dietary habits in obese adults, have reported improved weight loss outcomes [81,82] and glucose control [7]. Realistically, short intensive programs deliver crucial education and tools allowing informed decisions about health-related behaviors. Effective long-term application is, however, at the discretion of the individual. This may be problematic in adolescents who may wish to exercise autonomy in decision-making. Additionally, family/parental involvement is key for positive sleep behavior in pediatric populations [83] but may impede adolescent compliance, as this age group develops independence. Retention rates are an important consideration, although preliminary evidence indicates good adherence and retention rates in those with self-identified sleep problems [47] when motivation to change may be greater.

Delivery of sleep interventions require recognition of the problem coupled by effective tools based on sound psychological theories to address sleep improvement [64,65]. It is advisable for sleep experts, with a background in psychology, to deliver such programs, as per Wing et al. [52]. This may enhance success, particularly if interventions are supported by robust theories of behavior modification [84] and include targeting multiple lifestyle components known to exacerbate sleep loss, highlighted in this review. Careful study design is of great importance and randomized controlled trials can provide crucial evidence, but are currently limited, particularly in adolescents [51,52]. Aside from one study [52], most have assessed the efficacy of sleep improvement programs in small samples [47–51]. The findings from existing data are heterogeneous and so it may be premature to invest in larger randomized controlled trials without further pilot studies. A solid evidence-base of consistent findings is first required, incorporating regular assessments of objectively determined sleep. Sleep improvement programs should, in the first instance, be developed for homogeneous groups with identified sleep problems that affect daytime functionality so that improvements in objectively determined sleep can be examined at regular intervals. Should these demonstrate successful retention rates as well as sleep improvement, the next step is to examine the effects upon body weight, metabolic hormone regulation, and energy

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intake/expenditure. If the efficacy of sleep improvement can be shown to reduce obesity and/or diabetes outcomes, such as BMI, central adiposity, insulin resistance and/or glucose tolerance, then this may be a cost-effective addition for tackling these global epidemics.

Puberty and contemporary lifestyles exacerbate sleep loss

Prospective data have demonstrated significant biologically-determined delays in sleep initiation and subsequent sleep loss with advancing pubertal status [85,86]. Emerging evidence in young adolescents has shown that late circadian preference (later bedtimes and sleep onset), verified by wrist actigraphy, is not only associated with increasing BMI z-score but also poorer dietary habits [9]. Shifts in sleep timing and late circadian preference has been shown to impede healthy metabolic function in young adults [16,17] as well as those with type 2 diabetes [87]. Replication of these findings are now required in adolescent populations at risk of obesity and/or type 2 diabetes. Whilst hormonal alterations associated with puberty are not modifiable, environmental factors and lifestyle choices, shown to exacerbate sleep loss are, and should be incorporated into future programs aimed at improving sleep-related behaviors.

Technology use in adolescents

Technology use, specifically during the hours preceding bedtime, has been associated with a multitude of unfavorable subjective sleep outcomes in young adolescents [73]. Another study revealed significant linear associations between weekday sleep duration and all four technologies assessed [88]. Sleep duration had a strong direct effect on BMI ($\beta = -0.40$, $p < 0.01$) and more contemporary, portable technologies were indirectly associated with BMI, mediated by sleep duration [88]. The direct association between technology and obesity has been documented [19,88–90], however a number of studies have taken a positive approach and used technology to promote physical activity as a means of reducing obesity [91]. The complex relationship between technology use, obesity and sleep duration [88], is likely to be mediated by increased energy intake [92] and sedentariness [93]. Some have suggested that exposure to television advertisements promoting unhealthy foods and sugar-sweetened beverages, are contributing to the current obesity epidemic [94].

Mechanistically, the deleterious effects of technology upon sleep are purported to be the result of blue frequency light emission from devices, which challenges the circadian clock via the retino-hypothalamic tract and suppresses melatonin secretion [95]. Melatonin release is delayed in those with delayed sleep timings [96], which may result in shortened sleep duration, particularly during school nights when adolescents are required to wake early for academic commitments. Chronic exposure to blue frequency light emitted from electronic devices may therefore indirectly contribute to subsequent weight gain in adolescents through the downstream effects of sleep loss [73–75] with subsequent effects on metabolic hormone regulation [59] and feeding behavior [36,37,59]. Sleep improvement programs should encompass education about technology use timing and pre-bedtime avoidance. Adolescents are particularly vulnerable to light exposure near bedtime, which can exacerbate phase delay and sleep initiation [73]. In cultures where napping is more common [78], reduction in sleep pressure (homeostatic drive), because of sleep drive reduction when napping occurs, combined with technology use is likely to further exacerbate sleep phase delay.

Caffeinated/sugar-sweetened beverages

Sales of caffeinated/sugar-sweetened beverages and energy drinks have increased significantly in recent years [97]. Data show that consumption of these beverages before bedtime results in adverse sleep consequences [74,75]. Caffeine is an adenosine receptor antagonist [98] that increases sleep latency [99] and reduces SWS [100]. One study demonstrated an increase in caffeinated beverage consumption with age, showing that 85% of 12–18 y olds consume these beverages on a daily basis with a large proportion (46.6%) reporting ingestion between 15:00 and 20:00 h [74], with likely disruption to sleep onset, architecture, quality and duration. Recent cross-sectional evidence showed a significant inverse relationship between actigraphy-estimated sleep duration and energy density intake, added sugar as well as sugar-sweetened beverages [101]. Furthermore, variation of sleep duration, by just 10 min per night, was positively associated with intake of sugar-sweetened beverages $\beta = 0.20$, $p = 0.03$ [101].

A systematic review of randomized controlled trials revealed that caffeine ingestion resulted in 14–37% decreased insulin sensitivity in those with type 2 diabetes [102]. Whilst caffeine has been shown to modestly improve weight loss in obese adults [103], the time of ingestion is an important consideration so as to not interfere with sleep and hormone regulation. Given that the data are suggestive of caffeinated drink consumption after school hours in adolescents [74], this is a crucial component to target in future sleep improvement interventions.

Conclusion

The evidence supporting a link between sleep loss and obesity in adolescent populations is accumulating. Sleep should be optimized in adolescents to ensure positive health outcomes, but the current literature for efficacy of education programs to improve sleep is tentative, and the findings are inconsistent. Furthermore, only two programs have been conducted to assess obesity and/or metabolic outcomes in pre-adolescent/adolescent populations, in response to sleep improvement [47,59]. Larger, carefully developed, randomized controlled trials are required with regular, objective and prospective sleep assessment, which targets and measures potential alterations in multiple sleep features based on an individualized approach. This will help to determine the efficacy of such programs and facilitate investigation into the potential downstream effects on eating behaviors, physical activity and other lifestyle behaviors (technology use and intake of sweetened and/or caffeinated beverages) that promote obesity and metabolic disturbance.

Practice points

- Ensuring a balanced lifestyle, including prioritization of sleep is important for health and wellbeing.
- Chronic disruptions to optimum sleep in adolescent populations may result in weight gain and obesity/diabetes onset.
- Pubertal development results in sleep alterations, which are exacerbated by multiple lifestyle behaviors, such as:
  1. Technology use, particularly at bedtime, resulting in excessive light exposure and delays in melatonin release;
  2. Caffeinated/sugar-sweetened beverage intake, especially near bedtime, which can delay sleep onset.

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Research agenda

Sleep education targeted towards adolescent populations requires:

1. An approach that targets multiple lifestyle behaviors, and possibly incorporates parental involvement, while respecting adolescent need for autonomy;
2. Regular prospective assessment of objective sleep measures in the natural environment to verify feasibility and compliance;
3. Clearly defined outcome measures including alterations in body weight, metabolic hormones, and diabetes indicators;
4. Further evidence of its efficacy for inclusion into lifestyle programs to tackle obesity/diabetes mellitus.

Conflicts of interest

The authors have no conflicts of interest to declare.

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