2022-11-06

Circadian Misalignment and Childhood Obesity: An Unexplored Target for Intervention and Treatment

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For more than 20 years, childhood obesity has been considered a global pandemic (Malecka-Tendera & Mazur, 2006), with the cost (Sonntag et al., 2015; Hamilton et al., 2017) and prevalence (Ogden et al., 2016) only growing as time goes on. These stark increases were further exacerbated by lockdowns and restrictions caused by the Covid-19 pandemic. One study reported a 3% increase in childhood obesity in the United States one year after the original shutdowns (Dyer, 2021). Given that there were 74 million children living in the United States in 2019, these estimates suggest that 2.2 million children may be affected by this climb (Annie E. Casey Foundation, 2019). Even before Covid-19, obesity rates had been increasing for over a decade. For example, between 2007 and 2019, prevalence increased by 2.5% (16.8% in 2007 to 19.3%; Fryar et al., 2020). Similar increases have also been noted globally (Stavridou et al., 2021; Browne et al., 2021). This trend is concerning as childhood obesity has been associated with a multitude of negative short- and long-term health outcomes such as depression and anxiety (Morrison et al., 2015), low self-esteem and low self-reported quality of life (Halfon et al., 2013), increased risk of Type 2 Diabetes and heart disease (Bhave et al., 2003; Kim et al., 2020), and higher rates of comorbid conditions such as asthma (Di Genova et al., 2018), hypertension, and polycystic ovary disease (Balasundaram & Krishna, 2022).

Research addressing the ongoing pandemic of childhood obesity has pointed to sleep as a potentially potent variable underlying obesity (Córdova et al., 2018; Mazri et al., 2019; Sluggett et al., 2019). While the specific mechanisms driving this relationship continue to be debated (Krietsch et al., 2019), dietary factors are emerging as potentially critical mediators (Duraccio et al., 2019). Furthermore, sleep may have an especially profound influence on dietary factors and obesity during the teenage years. This is because adolescence represents a unique developmental period where inadequate sleep and circadian misalignment are both normal and encouraged. For example, early school start times, early morning extracurricular activities, increased independence in setting bedtimes, and rising use of social media can all contribute to a form of sleep deprivation known as social jetlag (Clarskadon et al., 1998). At the same time, innate sleep patterns naturally shift later (Carskadon et al., 1998; Carskadon, 2011), lifelong dietary habits are forming (Ogden et al., 2016; Skinner et al., 2016) and rates of obesity spike (Alberga et al., 2012; Larson et al., 2009). A definitive connection between insufficient sleep and circadian misalignment, dietary changes, and obesity may provide an essential tool for treating and preventing childhood obesity, especially if improved sleep hygiene and duration can disrupt the proposed pathway from poor sleep to obesity via obesity-causing dietary changes.

Current research shows consistent support for a relationship between sleep duration, diet, and obesity in adults (Dashti et al., 2015; Mazri et al., 2019) and adolescents (Al-Haifi et al., 2015; Hayes et al., 2018; Tambalis et al., 2018; Chaput et al., 2021); however, relatively few studies have examined the mechanisms contributing to this relationship. Limited available research in adolescents does support the hypothesized mechanism of a diet-mediated relationship between sleep and obesity. Specifically, when compared to themselves at healthy sleep durations, adolescents with shorter sleep durations are more likely to find foods rewarding (Duraccio et al., 2020; Duraccio, Zaugg, et al., 2019), have increased reward-related neural activation to food stimuli (Jensen et al., 2019), and spend more hypothetical money on food (Duraccio et al, 2020b). This heightened reward response influences daily behavior as sleep-restricted adolescents consume more carbohydrates, more foods with higher glycemic loads (e.g., sweet/desserts), and fewer fruits and vegetables (Duraccio et al., 2021; Ferranti et al., 2016).

Adolescents in shortened sleep conditions also show increased food consumption during late evening hours (Duraccio et al., 2021) and have decreased inhibitory control in the presence of food images (Duraccio et al., 2019b; Jensen et al., 2019). In this vein, a study of young adults found that those experiencing poor sleep were more likely to deal with negative emotions by overconsuming food (Zerón-Rugerio et al., 2022).

Research examining the relationship between sleep and obesity in older adults is scarce. To my knowledge, only two such studies have been conducted: one in Korea (Kim & Lee, 2019) and one in China (Fan et al., 2020). These studies did find both sleep duration and sleep quality to be negatively correlated with a healthy diet, but additional research is needed to connect these findings directly to obesity. Preliminary findings do suggest that changes in dietary habits may drive the relationship between short sleep duration and increased risk of obesity (Duraccio et al., 2019). If confirmed, these findings enhance the justification for including sleep as an intervention target for adults with obesity and also highlight the potential for early interventions in cases of pediatric obesity.

A major limitation of the current research in both adult and pediatric populations is its failure to consider the influence of circadian factors on sleep and diet. In fact, relatively little literature has evaluated the relationship between circadian misalignment and dietary habits. A study in adults has found that circadian misalignment is associated with higher dietary intake (Baron et al., 2016). Preliminary work also suggests that adolescents lower their caloric consumption following an "early to bed" sleep extension protocol, although this was only true if their chronotype (preferred sleep timing) was aligned with the early timing of the assigned sleep intervention (Beebe et al., 2015). Those with a later chronotype actually consumed more calories following the sleep extension period (Beebe et al., 2015). Chronotype has also been associated with other dietary patterns, with "eveningness" (the tendency for a later bedtime; sometimes referred to as being a "night owl") correlating with poorer nutritional intake and missed breakfasts in both college students (Teixeira et al., 2017) and other adults (Mazri et al., 2019). No known studies have considered how preferred chronotype aligned with participants' actual sleep-wake timing; however, one study did examine misalignment in young adults and found an association with increased BMI, lower intake of fruits and vegetables, and more missed breakfasts (Zerón-Rugerio et al., 2019). Given the natural shift in circadian rhythms that occurs following puberty (Crowley et al., 2018), it may be especially pertinent to consider circadian alignment as a potential treatment target in adolescent obesity, even when other measures of sleep quality such as duration or depth appear to be within healthy ranges.

Currently, the most common treatments for childhood obesity focus on exercise and dietary habits. In rare cases, medical interventions such as gastric bypass surgeries or appetite-suppressing medications may also be deemed necessary. Current behavioural interventions are largely grounded in cognitive-behavioural therapy (CBT), although animal-assisted therapy (AAT) is also used (Boisvert & Harrell, 2015). Studies have shown CBT to be quite effective in treating obesity (Grassi et al., 2017), but few recent studies have looked at its effectiveness in improving diet. One study of 110 adolescents found that at a 6-month follow-up, those treated with CBT (N=55) showed significant improvement in dietary quality (eating more fruits, vegetables, etc.,) when compared to a control group ($p < 0.001$), but demonstrated no significant change in overall caloric intake (Miri et al., 2019). Importantly, the presence of positive factors such as a healthy diet are highly debated as predictors of adolescent obesity (Carlson et al., 2012) while negative factors such as excess energy intake and poor eating habits are much more consistently predictive (Huang & Qi, 2015; Liberali et al., 2020). While CBT has been reliably shown to improve quality of life and exercise habits in obese adults and children (Kang & Kwack, 2020), there is little evidence suggesting the effectiveness of CBT in improving diet.

Recent studies have indicated that CBT is more effective at facilitating weight loss when paired with lifestyle modifications such as diet and exercise (-1.7kgs with CBT, -4.9kgs with CBT plus lifestyle modification; Kheniser et al, 2021). With these amplifying effects in mind, new forms of CBT developed specifically for obesity (CBT-OB) pay special attention to dietary and exercise habits (Dalle Grave et al., 2020). Since sleep has also been associated with obesity (Beccuti & Pannain, 2011; Ogilvie & Patel, 2017) and dietary outcomes (Dashti et al., 2015, Sluggett et al., 2019), it is crucial that sleep interventions are also part of the conversation.

Sleep Duration and Diet

Historically, research on the connection between sleep and diet has focused on sleep duration rather than on circadian alignment. Sleep duration is typically defined as the total amount of time someone spends asleep during a nocturnal sleep episode and is frequently measured using questionnaires, sleep diaries, actigraphy, or polysomnography (Kline, 2013). Sleep duration has been associated with dietary outcomes in both adult (Dashti et al., 2015) and pediatric populations (Sluggett et al., 2019).

Sleep Duration and Diet in Adults

Sleep duration has been consistently identified as a predictor for dietary outcomes in adults, with length of sleep being inversely correlated with dietary quantity (Dashti et al., 2015) and quality (Chaput 2014; Dashti et al., 2015).

Dietary Quantity.

In contrast with two early studies that found no significant correlation between sleep duration and dietary intake (Nedeltcheva et al., 2008; Schmid et al., 2009), recent research agrees that reduced sleep duration is associated with increased dietary intake. For example, one study found that after only one night of restricting sleep to roughly four hours, men consumed 22% more calories than they did after eight hours of sleep (Brondel et al., 2010). Despite this increased energy intake, they also reported feeling significantly hungrier ($P < 0.001$) in the restricted sleep condition (Brondel et al., 2010). While this study's sample was quite small ($N = 12$), its results have been replicated many times. One replication ($N = 17$) restricted male participants to two-thirds of their typical sleep duration for eight days/nights and found that caloric intake increased by an average of 559 calories/day (Calvin et al., 2013). Another study examined both men ($N = 15$) and women ($N = 15$) across 10 nights of sleep, restricting them to four hours of sleep for five of the nights and then allowing habitual sleep duration the other five nights, with the order of the sleep conditions being randomly assigned (St-Onge et al., 2011). They reported a 593 calorie/day increase during the restricted sleep condition. (St-Onge et al., 2011). When controlling for both race and sex, another study found that during sleep restriction, men's consumption increased more than women's ($d = 0.62$), with average caloric intake increasing by 533 calories/day across sexes (Spaeth et al., 2014). There was no significant difference in this effect between white and African American participants (Spaeth et al., 2014).

Dietary Quality.

Findings suggesting an inverse relationship between sleep duration and dietary quality are even more consistent. The aforementioned study conducted by Brondel et al. (2010) reported significant increases in fat consumption (41 ± 6% of caloric intake; $P < 0.01$) during sleep restriction and the findings of St-Onge et al. (increased fat consumption of 20.7 ± 37.4 g; $P = 0.01$; 2011) support this connection. Fat intake has been associated with increased insulin resistance in adults (Dhaka et al., 2011; Hernández et al., 2017), which in turn is linked to obesity (Qatanani & Lazar, 2007; Kolb et al., 2018).

Another study assigned 61 participants (42 female) to six weeks of adequate sleep (≥7 h/night) followed by six weeks of restricted sleep (Barragan et al., 2022). Even with a modest reduction of 1.5 hours from typical sleep durations, the restricted sleep condition was associated with decreased dietary quality, namely, significantly increased consumption of fat and sugar (Barragan et al., 2022). Other studies have reported similar increases in sugar intake during restricted sleep, as well as increased snacking behaviours (Heath et al., 2012; Chaput, 2014), both of which have been shown to predict BMI and obesity (Bo et al., 2015; Ma et al., 2016). As evidenced by these findings, it is widely accepted that sleep duration negatively affects dietary quality which in turn can lead to weight gain and eventual obesity.

Sleep Duration and Diet in Children and Adolescents

The associations between sleep duration and diet quantity and quality have also been observed in children and adolescents, although fewer studies have examined these relationships in younger age groups.

Dietary Quantity.

Similar to research in adults, multiple studies reported an association between short sleep duration and quantity of food consumption. Two studies, one in Italy (N = 1586, aged 11-14) and one in China (N = 3103, aged 11-13), reported an association between short sleep duration (<7h/night) and increased snacking behaviours, although, as was seen in adult studies, the Chinese study found the association to be significant only in males (Spaeth et al., 2014; Ferranti et al., 2016; Lu et al., 2014). A Danish study of 676 children ages 8-11 also found that sleep duration is inversely associated with caloric intake (Kjeldsen et al., 2013), and several other studies supported these findings (Ferranti et al., 2016; Sluggett et al., 2019). Overall, a meta-analysis found 7/10 of available pediatric studies support an association between caloric intake and short sleep duration (Córdova et al., 2018). This analysis also supported a relationship between snacking behaviours and short sleep duration (Córdova et al., 2018). While research on dietary quantity is not as extensive in pediatric populations as it is in adults, available results strongly suggest a relationship between sleep and diet.

Dietary Quality.

An analysis of data collected from 177,000 children and adolescents (51% male) in Greek school systems found that adolescents and children who reported insufficient sleep (<8h/night and <9h/night, respectively) were more likely to engage in a myriad of unhealthy dietary behaviours including skipping breakfast (OR = 1.30), regularly consuming fast food (OR = 1.35), and regularly consuming sugary foods and desserts (1.32; Tambalis et al., 2018). These findings are well supported globally. For instance, a Norwegian study found short sleep duration predicts greater consumption of sweets (OR = 1.96; Stea et al., 2014). A series of studies conducted by Chaput and colleagues (2018) in 12 countries including the United States found that short sleep duration correlates with increased consumption of sugar-sweetened beverages. Similar to the research in adults, these studies consistently suggest a relationship between sleep and dietary quality in this cohort.

As the presence of connections between sleep and dietary quality and quantity become increasingly clear in both children and adults, current research continues to explore potential mechanisms behind these relationships and determine if the nature of these associations are causal (Dashti et al., 2015). While many studies have pointed to sleep duration as the most important factor of sleep influencing dietary habits, the results are largely correlative. Future research will need to move away from cross-sectional observations to controlled experiments to determine the true impact of sleep duration on dietary quality. More recent research also suggests that such focus on sleep duration has led to overlooking a potentially equally, if not more, impactful aspect of sleep that affects diet: circadian alignment (Baron et al., 2016).

Circadian Misalignment and Diet in Adults

Studies examining the relationship between circadian misalignment (CM) and diet in adults are scarce. The few studies that do examine CM tend to focus on how chronotype (circadian preference) itself relates to diet rather than on addressing participants' behavioural alignment with their biological chronotype. Circadian preference is best estimated using the timing of melatonin secretion, a method referred to as dim-light melatonin onset (DLMO; Burgess et al., 2015); however, due to the high expense of using DLMO in study procedures, most existing research relies on the Morningness/Eveningness Questionnaire (MEQ) or an equivalent self-report survey to assess circadian alignment. The MEQ was normed using oral temperature curves (Horne & Ostberg, 1967) and has been shown to be an accurate measure of circadian preference (Sack et al, 2007). Even still, it is not as accurate as DLMO and thus heavy reliance on the MEQ is a limiting factor in the existing research. Despite the MEQ's limitations, research with it consistently suggests that CM has an important role to play in dietary practices.

The most commonly reported relationship between CM and diet is an association between those with a preference for later sleep and wake times (dubbed "eveningness" or "night owls") and missing breakfasts, a practice that has consistently been associated with increased BMI, waist circumference, and obesity (Watanabe et al., 2014; Ma et al., 2020). One study of 721 Brazilian undergraduates found that evening types were significantly more likely to miss breakfast when compared to morning and intermediate types ($p = 0.02$). A Turkish study of 142 students reported similar findings, with 60% of participants with an evening preference claiming to regularly skip breakfast (Toktas et al., 2018). Another study found that German students (N = 471) with evening types went significantly longer without eating in the mornings than those with morning types ($F = 17.54$, $p < 0.001$; Meule et al., 2012).

These results have been replicated consistently, but studied samples have been limited almost exclusively to student populations (Sato et al., 2011; Teixeira et al., 2017, Zerón-Rugerio et al., 2019), with the exception of one study which found similar results in diabetic patients at a Chicago care center (Reutrakul et al., 2014), and a recent study which replicated those findings in Italian adults (Lotti et al., 2022). Many of the student studies also reported a relationship between eveningness and consumption of high-fat and high-sugar foods, as well as eveningness and caloric intake generally, although a review of 36 studies by Mazri and colleagues found that across the literature, only sugar consumption was consistently higher for evening types (2019). While these results certainly suggest a relationship between circadian preference and dietary habits, the focus on college populations is a significant limitation that prevents the full generalization of these findings.

Another major limitation in available research is the focus on circadian preference rather than circadian alignment. None of the above studies assessed participants for their actual circadian timings using DLMO or any other biological methods. Circadian alignment and sleep disruptions have been associated with a plethora of physiological deficits, including nutritionally impactful changes such as decreased insulin sensitivity (Potter et al., 2016). Despite this apparent importance, to my knowledge, only one study examined circadian alignment and dietary outcomes directly in adults. This study (N = 97; 61 female) used DLMO to measure circadian timing and found that later circadian timings were associated with higher % body fat ($p = 0.02$), and circadian misalignment was associated with increased caloric intake (P=0.049), carbohydrate intake (P=0.04), and meal frequency (P=0.03) for both males and females (Baron et al., 2016). While this is an isolated study, in the context of the existing research on circadian preference, the results suggest that circadian misalignment may well be an intervention target for treating and preventing obesity in adults. However, more research is needed before any firm conclusions can be made within this age group.

Circadian Misalignment and Diet in Children and Adolescents

The trends in the relationship between CM and diet seen in the research for children and adolescents show a similar story to those found in adults; however, research is even more sparse. Like adult studies, research in pediatric populations has mainly focused on how chronotype relates to dietary habits. A study of young adolescents in the UK (N = 511, aged 11-13) found that late chronotype was associated with consumption of unhealthy snacks ($p < 0.01$), late-night snacking ($p < 0.01$), late-night caffeine consumption ($p < 0.01$), and inadequate daily consumption of fruits/vegetables ($p = 0.01$; Arora & Taheri, 2014). A study of German youth (N = 152, aged 11-16) also found a relationship between late chronotype and consumption of snacks and caffeinated beverages, but no association between late chronotype and consumption of fruits/vegetables (Roßbach et al., 2017), suggesting that chronotype may contribute to more unhealthy dietary behaviours, but not fewer healthy ones. More research is needed to confirm these findings.

While the research is scarce, there has also been evidence that chronotype affects meal skipping in children in a similar manner to adults. A study of 469 children in Hong Kong (261 male, aged 7-11) found that boys, but not girls, with later chronotypes were significantly more likely to miss breakfast (OR = 14.78, $p = 0.01$; Yu et al., 2020). This study was conducted with the goal of replicating the findings of two studies that were conducted in the United States (N = 119, aged 9-15, 91 female; Thellman et al., 2017) and Australia (N = 2200, aged 9-16; Golley et al., 2013), both of which found an association between later bedtimes and missing breakfast, although neither study noted any gender differences in their findings. Notably, the latter two studies did not use any objective measures of chronotype, and more research including physiological metrics is needed to corroborate these results.

To my knowledge, no studies have used the gold-standard DLMO to measure circadian alignment in children or adolescents. Thus, a relationship between CM and dietary outcomes can only be inferred from the existing results in adults as well as the research suggesting an association between chronotype and dietary outcomes in children and adolescents by use of other, and potentially less reliable, methods. In order to determine if CM is a valid intervention target for reducing obesity in both pediatric and adult populations, future research should focus on using DLMO to measure circadian timing and on correlating preferred and actual sleep timing with dietary and other health outcomes.

Conclusion

Sleep has long been associated with a multitude of health outcomes (Medic et al., 2017). Recent research has consistently related both sleep duration and timing to dietary outcomes that predict BMI and obesity (Dashti et al., 2015; Córdova et al., 2018; Ma et al., 2020) in adult and pediatric populations. In adults, sleep timing and chronotype have been associated with increased caloric intake (Baron et al., 2016), increased snacking behaviours (Heath et al., 2012; Chaput, 2014), increased consumption of high-sugar and -fat foods (Barragan et al., 2022), and other unhealthy dietary habits such as skipping meals (Sato et al., 2011; Teixeira et al., 2017, Zerón-Rugerio et al., 2019). Few studies have examined similar effects in children and adolescents, but preliminary findings suggest that sleep timing and chronotype are associated with increased consumption of sugary foods and drinks (Arora & Taheri, 2014; Roßbach et al., 2017), skipping breakfast (Golley et al., 2013; Thellman et al., 2017, Yu et al., 2020), increased snacking (Arora & Taheri, 2014; Roßbach et al., 2017), and increased caffeine consumption (Arora & Taheri, 2014). This convergence suggest that sleep-based interventions may be an effective approach to curbing the epidemic that childhood obesity has become. Despite these findings, a systematic review of sleep interventions aimed at reducing BMI by increasing sleep duration found that out of eight trials, only one was successful in significantly reducing BMI (Yoong et al., 2016). This suggests that addressing sleep duration alone is not enough. Future research should assess the efficacy of targeting circadian alignment in sleep-based interventions for treating BMI and obesity through diet, and additional research should explore how CM relates to other obesity-related health outcomes such as physical activity.

While research on sleep and diet as key moderators of obesity is promising, it is not without its limitations. Only one known study measured circadian alignment using the golden standard DLMO in adults (Baron et al., 2016), and no studies were found using DLMO in adolescents or children. It is paramount that future studies assessing the relationship between sleep and dietary outcomes use gold-standard methods such as DLMO to assess circadian alignment and determine its role in dietary behaviours. Furthermore, all studies examining the impact of sleep on dietary outcomes in adolescents have used dietary recalls to assess dietary patterns (Duraccio et al., 2021; Baron et al., 2016, Beebe et al., 2015). An alternative and compelling methodological approach to measuring dietary intake is observing foods consumed while adolescents are in a laboratory setting. In-vivo dietary intake assessments could overcome key limitations of the dietary recall interviews (e.g., recall errors and biases) by capturing dietary consumption precisely, with low burden, and with minimal bias.

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