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Effect of Sleep on Weight Loss and Adherence to Diet and Physical Activity Recommendations during an 18-month Behavioral Weight Loss Intervention

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Abstract

Background/Objectives: To examine the association between indices of sleep quantity and quality with dietary adherence, physical activity adherence, and weight loss during a behavioral weight loss intervention.

Methods: Adults (n=156) with overweight and obesity (40±9 years, 84% female, BMI: 34.4±4.2 kg/m^2) participated in an 18-month behavioral weight loss intervention which prescribed a reduced calorie diet (1200-1800 kcal/d) and increased physical activity (300 min/wk). Body weight, indices of sleep (SenseWear armband; SWA), energy intake (EI, 3-day food records), and moderate-to-vigorous physical activity (SWA) were measured at baseline, 6, 12, and 18 months. Linear mixed effects models examined the association between sleep and weight change over time. Additional models were adjusted for covariates including age, BMI, sex, race, ethnicity, study completion, randomization, EI, and physical activity. Secondary analyses examined the association between sleep and adherence to diet and physical activity recommendations.

Results: Mean weight loss was 7.7 ± 5.4, 8.4 ± 7.9, and 7.1 ± 9.0 kg at 6, 12, and 18 months, respectively. Lower sleep efficiency, higher wake after sleep onset (WASO), more awakenings,

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and higher sleep onset latency (SOL) were significantly associated with attenuated weight loss ($p<0.05$). Lower sleep efficiency, more awakenings, and higher SOL remained significantly associated with blunted weight loss after adjustment for covariates ($p<0.05$). Later waketime, longer time in bed, longer sleep duration, higher WASO, more awakenings, and higher SOL were associated with lower odds of achieving ≥300 min/wk of moderate-to-vigorous physical activity, adjusted for covariates (FDR $p<0.05$).

Conclusions: Future studies should evaluate whether incorporating strategies to improve sleep health within a behavioral weight loss intervention leads to improved adherence to diet and physical activity recommendations and enhanced weight loss.

Keywords

obesity; exercise; lifestyle treatment

INTRODUCTION

It is estimated that 42.4% of US adults have obesity (BMI ≥30.0 kg/m^2) (1). Obesity is associated with cardiovascular disease (2, 3), type 2 diabetes (4), and some forms of cancer (5, 6). The cornerstone of obesity treatment is lifestyle modification which includes a reduced calorie diet, increased physical activity, and behavioral support to promote adherence to the diet and physical activity recommendations (7). This strategy typically results in on average 5-10% weight loss over one year (7); however, a significant number of individuals are unable to lose and maintain weight loss long-term (8–12). Thus, identifying strategies that improve the long-term efficacy of behavioral weight loss programs are needed.

Sleep has recently been recognized as an important factor in body weight regulation (13, 14). Epidemiological evidence suggests that short sleep and long sleep duration are associated with an increased risk of obesity and weight gain (15, 16). Furthermore, poor sleep quality is associated with obesity (17–21). Suboptimal sleep, including short sleep duration and poor sleep quality, may lead to both physiological and behavioral adaptations that make weight loss and weight loss maintenance more difficult. For example, acute sleep restriction (5 days with a 5h sleep opportunity) resulted in increased energy intake (EI) by ~200 kcals per day compared to normal sleep (5 days with 9h sleep opportunity) (22). If sleep is curtailed over longer periods of time, it could result in future weight gain. Within the context of caloric restriction similar to what is recommended for weight loss, sleep restriction led to attenuated fat loss, increased lean mass loss, and increased hunger (23). These collective studies suggest that both sleep duration and sleep quality may play an important role in energy balance and body weight regulation.

Previous studies examining the effect of sleep on weight loss during lifestyle modification have yielded inconsistent results. Some studies have found that fewer awakenings at night (24), adequate sleep duration (6-9 h/night) (25–27), self-reported sleep quality (25, 26), and overall sleep health (a composite measure based on six dimensions of sleep) (28) are associated with greater weight loss during a behavioral weight loss intervention. In contrast, other studies have found no association between indices of sleep and weight loss during a behavioral weight loss intervention (29–31). However, none of these prior studies have included both objective measures of sleep and measures of long-term weight loss (>12 months) during a comprehensive behavioral weight loss intervention. In addition, few studies have examined the association between characteristics of sleep and adherence to critical components of the behavioral weight loss intervention (diet and physical activity recommendations) (32–34).

The primary purpose of this secondary analysis was to examine the association between indices of sleep and weight change during an 18-month behavioral weight loss intervention. In addition, we examined the association between indices of sleep and adherence to the dietary and physical activity recommendations. We hypothesized that shorter sleep duration and poorer sleep quality would be associated with attenuated weight loss and reduced adherence to the dietary and physical activity recommendations.

METHODS

Participants

We conducted a secondary analysis of 170 adults (18-55 years) with overweight or obesity (BMI 27-42 kg/m^2) who participated a an 18-month comprehensive behavioral weight loss intervention which included a calorie-restricted diet, increased physical activity (including provision of supervised exercise), and behavioral support (NCT01985568). Methods and primary findings of the study have been published previously (35). Briefly, the study was designed to determine the optimal time to initiate exercise during a behavioral weight loss intervention (at the onset of the behavioral weight loss intervention vs. 6 months later following initial weight loss from diet-only). This study was approved by the Colorado Multiple Institutional Review Board and all participants provided written informed consent prior to participation. Participants were recruited via campus-wide emails, flyers, and mailings. Interested individuals who met preliminary criteria were invited for an on-site visit which included a health history and physical exam by the study physician. Individuals were excluded if they had a history of cardiovascular and metabolic diseases, cancer, previous weight loss surgery, >5% change in body weight during the previous 6 months, self-reported >150 minutes/week of moderate intensity exercise, current use of medications known to affect appetite, weight, or energy metabolism, or any medical conditions that contraindicated exercise. During the health history and physical exam with the study physician participants were queried about diagnosed sleep disorders. Five individuals (3.1%) had diagnosed sleep apnea at baseline.

Behavioral Weight Loss Intervention

Participants were randomized in a 1:1 ratio to one of two behavioral weight loss intervention groups: Standard or Sequential. Both groups received an identical 18-month group-based behavioral weight loss program and a 6-month supervised exercise program. The only differences between groups was the timing of the initiation of the supervised exercise program. Standard received the supervised exercise program during months 0-6 and Sequential received the supervised exercise program during months 7-12. The supervised exercise program included complimentary access to a fitness facility and progressed from

3 to 5 days per week at moderate intensity (65-75% maximal heart rate) with sessions progressing from 20 to 60 minutes (60 min/wk to 300 min/wk). Upon completion of the 6 month supervised exercise programs, participants were recommended to continue engaging in ≥300 min/wk moderate intensity physical activity until study completion and were provided complimentary access to the fitness facility throughout the study. All participants were prescribed a calorie-restricted diet (1200-1800 kcal/d) designed to produce clinically significant weight loss (≥5%). Calorie recommendations were individualized based on estimated resting metabolic rate (36) and were not adjusted during the study. Both groups received group-based behavioral support focusing on promoting adherence to both diet and activity recommendations. Group-based behavioral support was provided weekly for weeks 0-20, every other week for weeks 21-26, and monthly for weeks 27-78. Additional details about the behavioral weight loss intervention have been described previously (35).

Assessments

Assessment visits were completed at baseline (prior to enrollment in the behavioral weight loss program), 6, 12, and 18 months. Height was measured to the nearest 0.1 cm using a wall-mounted stadiometer at baseline only. Body weight was measured to the nearest 0.1 kg using a calibrated digital scale (Tanita® PH-740; Arlington Heights, IL). Body composition, including fat mass and lean mass, were measured using dual energy x-ray absorptiometry (Hologic QDR series; Bedford, MA).

Sleep and physical activity were assessed using the SenseWear Mini Armband (SWA, BodyMedia Inc; Pittsburgh, PA). The SWA uses multiple inputs (accelerometry, skin temperature, galvanic skin response) to determine wear time, sleep, and intensity of waking activity. Participants were asked to wear the SWA for 24h/day for 7 consecutive days except for showering, bathing, and swimming. Data from the SWA were considered valid for participants that provided ≥4 valid days including ≥1 weekend day. A day was classified as valid if the device was worn for ≥22.8 h/day (95% wear time). Days for sleep data were considered as 12:00 until 11:59 the next day; days for physical activity data were defined as 00:00 until 23:59. Indices of sleep duration and quality were created using the SWA and an open-source program (https://github.com/graulaurak/sleep). Indices included bedtime, waketime, midpoint of sleep, regularity, sleep efficiency, sleep duration, time in bed (TIB), wake after sleep onset (WASO), sleep onset latency (SOL), and number of awakenings. Bedtime was defined as the time the participant began lying down prior to sleep. Waketime was defined as the first time the participant was no longer lying down following sleep, which was not followed by more sleep. TIB was defined as the rest interval from bedtime until waketime. Sleep duration was defined as the sum of minutes classified as sleep during TIB. Midpoint of sleep was defined as halfway point between sleep onset and sleep offset. Sleep regularity was defined as the standard deviation of waketime. Sleep efficiency was defined as the percent of minutes defined as sleep between bedtime and waketime. WASO was defined as the sum of minutes classified as awake after sleep onset. SOL was defined as the number of minutes from bedtime until sleep onset. Number of awakenings was defined as the independent number of awake events across the night. Sleep diaries were not collected in this study. The SWA was also utilized to measure moderate-to-vigorous physical activity (MVPA; defined as the sum of all waking minutes ≥3.0 metabolic equivalents (METs). For determining adherence to the physical activity recommendation, bout-MVPA was calculated as MVPA accumulated in bouts of ≥10 consecutive minutes allowing for 20% of the bout to be classified as <3.0 METs (35). Participants accumulating ≥300 min/wk of physical activity were considered adherent to the physical activity recommendation. The SWA has been validated for measuring MVPA (37–39) and indices of sleep (40–42).

EI (kcal/d) was measured using 3-day food records. Food records were analyzed by trained staff blinded from randomization assignment from the Colorado Clinical and Translational Sciences Institute (CCTSI) Nutrition Core using Nutrition Data System for Research Software (Nutrition Coordinating Center, University of Minnesota; Minneapolis, MN). Participants had individual calorie goals designed for weight loss (1200-1800 kcal/d) based upon estimated resting energy expenditure (36). Adherence to this recommendation was defined as having a mean EI (kcal/d) less than or equal to their individual calorie goal.

Statistical Analysis

Statistical analyses were performed using SAS 9.4 (SAS System for Microsoft; SAS Institute Inc., Cary, NC). Baseline characteristics were summarized as means and standard deviations for continuous measures, and count/percent of total for categorical measures. Separate random intercept linear mixed effect models, with unstructured covariance matrices, were used to assess the association between each measure of sleep and weight change. The outcome was weight change from baseline (i.e., weight at 6 months – baseline, weight at 12 months – baseline, and weight at 18 months – baseline). Models utilized the sleep variables at 6, 12, and 18 months as predictors of weight change from 0-6, 0-12, and 0-18 months, respectively. Model 1 included the sleep measure of interest, study month, and baseline weight. The interaction between each measure of sleep and study month (sleep variable*month) was assessed and included if $p<0.05$. Model 2 included everything from Model 1 and adjusted for age, BMI, sex, race, ethnicity, study completion (i.e., individual completing month 18 measures), and intervention arm. Model 3 included everything from Model 2 and further adjusted for mean energy intake (kcal/d) and total MVPA (min/wk). In the absence of an interaction between sleep and time, the main effect of sleep is interpreted as the average change in weight from baseline, given a 1 unit increase in sleep, while adjusting for baseline weight and other covariates. A p-value of <0.05 was considered statistically significant for the primary analysis. Secondary analyses utilized similar models as above (Model 1 and 2) to examine the association between measures of sleep and change in fat mass and lean mass from baseline. For adherence to physical activity recommendations and adherence to EI recommendations, random intercept generalized linear mixed models with a binary distribution and a log link function were used. To be included in the MVPA adherence analysis, participants needed to have both a valid sleep and MVPA data at any one timepoint. To be included in the EI adherence analysis, participants needed to have valid sleep and EI data at any one timepoint. These secondary analyses included both the original p-values and false discovery rate (FDR) multiple testing adjusted p-values (FDR p-value), with FDR p-values <0.05 regarded as statistically significant. For the physical activity adherence analysis, data were aligned, such that each randomized group had equal exposure to the supervised exercise intervention (months 0, 6, and 12 for Standard; months 0, 12, and 18 for Sequential). To examine the inter-relatedness of each sleep variable Spearman correlations were performed at 0, 6, 12 and 18 months (Supplemental Table 4–7). An *a-priori* power calculation was not performed for this analysis. The study was powered for its primary outcome of weight change (3 kg between group difference), which required 85 participants per group (n=170) (35). A sensitivity analysis was performed to examine whether excluding participants with diagnosed sleep apnea (3.1% of participants) at baseline altered the significance of the models, but results were unchanged. We also examined whether there was an interaction between indices of sleep and age; however, these interactions were not significant in any of the models.

RESULTS

Figure 1 illustrates inclusion/exclusion of enrolled participants in these analyses. The baseline demographics of participants included in this analysis (n=156) are reported in Table 1. As reported previously, there were no differences in weight loss between the Standard and Sequential intervention groups at 18 months. Mean weight losses, including all participants, were 7.7 ± 5.4 kg, 8.4 ± 7.9 kg, and 7.1 ± 9.0 kg at 6, 12, and 18 months, respectively. The number of participants who were adherent to the MVPA recommendation was highest at 6 months and decreased over time (6 months: 59%; 12 months: 47%; 18 months: 29%). In contrast, the number of participants who were adherent to the EI recommendation was highest at 12 and 18 months (6 months: 31%; 12 months: 53%; 18 months: 53%). Descriptive sleep characteristics across the 18-month intervention are included in Supplemental Table 1.

Associations between Indices of Sleep and Weight Change

In all three models, higher SOL and lower sleep efficiency were associated with attenuated weight loss (Table 2). There were significant interactions between WASO and study month in Models 1 and 2. Higher WASO was associated with attenuated weight loss at 18 months. There were significant interactions between awakenings and study month in all three models. More awakenings were associated with attenuated weight loss at 18 months. The associations between sleep and weight loss did not vary by age (p>0.05).

Associations between Indices of Sleep and Adherence to the MVPA Recommendation

Associations between each measure of sleep and adherence to MVPA recommendations over time are presented in Table 3. In Model 1, TIB was associated with reduced odds of adhering to the 300 min/wk MVPA recommendation over time (FDR p=0.03), such that for every hour increase in TIB, the odds of meeting the physical activity recommendation decreased by 31%. For every 10-minute increase in SOL, the odds of adhering to the MVPA recommendation decreased by 43% (FDR p=0.03). In model 2, waketime, sleep duration, TIB, SOL, WASO, and awakenings were associated with reduced odds of adhering to the MVPA recommendation over time (FDR p<0.05). Specifically, every 1-hour delay in waketime was associated with 32% reduced odds of meeting the MVPA recommendation. Every 1-hour increase in sleep duration and TIB was associated with 33% and 41% reduced odds of meeting the MVPA recommendation. Higher SOL (per 10 minutes), higher WASO (per 10 minutes), and more awakenings (per 5 events) were associated with 10%, 25%, and 47% reduced odds of meeting MVPA recommendation.

Associations between Indices of Sleep and Adherence to the EI Recommendation

Associations between each measure of sleep and adherence to EI recommendations over time are presented in Table 4. In Model 1, WASO was associated with adherence to the EI recommendation (FDR p=0.03) such that a 10-minute increase in WASO was associated with 10% increased odds of adhering to the EI recommendation. This was no longer significant in Model 2 (FDR p=0.07).

Associations between Indices of Sleep and Body Composition Change

Associations between measures of sleep and changes in fat mass and changes in lean mass are presented in Supplemental Table 2 and Supplemental Table 3, respectively. Associations between measures of sleep and fat mass change were similar to those observed with change in body weight. Higher SOL was associated with attenuated fat mass loss in Models 1 and 2. There were no significant associations between indices of sleep and change in lean mass.

DISCUSSION

This study examined the association between indices of sleep duration, timing, and quality with dietary adherence, physical activity, and weight loss during an 18-month behavioral weight loss intervention. We found that lower sleep efficiency, higher WASO, more awakenings, and higher SOL were associated with attenuated weight loss. Lower sleep efficiency, more awakenings, and higher SOL remained significantly associated with blunted weight loss even after adjustment for covariates including EI and MVPA. In addition, we found that later waketime, greater sleep duration, greater time in bed, higher WASO, more awakenings, and greater SOL were associated with reduced odds of meeting the MVPA recommendation of ≥300 min/wk after adjustment for covariates. Moreover, we found that higher WASO was associated with reduced odds of meeting the EI recommendation in the unadjusted model. These findings suggest that aspects of sleep health may influence the effectiveness of a behavioral weight loss intervention.

Interestingly, we found that several aspects of sleep that fall into the domain of sleep continuity were associated with weight loss during a comprehensive behavioral weight loss intervention; however, sleep duration was not. Previous studies examining the association between components of sleep and weight change within a behavioral intervention have yielded inconsistent findings. There are several possible reasons for these discrepant findings including differences in the behavioral support program, differences in the study population (age, sex, BMI), varying duration of intervention and follow-up, and differences in the measurement of sleep quantity, quality, and timing (self-report vs. actigraphy). Chang et al. found that sleep duration, sleep quality, and sleep disturbance were not associated with weight change in 16-week intervention aimed at prevention of weight gain (30). Two other studies similarly found no association between sleep and weight loss during a behavioral weight loss intervention (29, 31). In contrast, several studies have found that components of sleep quality including greater sleep duration variability (27), more wake episodes across the night (24), lower subjective sleep quality (25), sleep irregularity (28), and later sleep timing (28) were associated with attenuated weight loss during a behavioral weight loss program. We found that higher SOL and more awakenings were associated with attenuated weight loss. Further, higher sleep efficiency was significantly associated with greater weight loss after adjustment for relevant covariates including EI and MVPA. This suggests that sleep efficiency is independently associated with weight loss during a behavioral weight loss intervention. These collective findings highlight the importance of sleep continuity and quality for bodyweight regulation. Strategies to enhance sleep continuity and quality during a behavioral weight loss may improve weight loss outcomes; however, a randomized prospective trial is needed.

Both long (43) and short sleep (16) are associated with obesity risk. Within the context of a behavioral weight loss intervention both short (44) and long sleep (25, 44) have also been associated with attenuated weight loss. Moreover, Alfaris et al. found that individuals who lost ≥5% body weight during a behavioral weight loss intervention increased sleep duration by ~20 min/night which was significantly more than individuals who lost <5% bodyweight (45). Other studies have found no association between sleep duration and weight loss (24, 27–31). Results of the current analyses align with these studies, finding no association between sleep duration or TIB and weight loss during an 18-month behavioral weight loss intervention. The lack of an association between sleep duration and weight loss is somewhat surprising considering the epidemiological link between sleep and obesity risk. It is possible that we failed to observe an association between sleep duration and weight loss in part due to our smaller sample population and minimal number of participants with short (n=35, 22% with <6 h/night) and long (n=3, 2% with >9h/night) sleep duration at baseline.

In addition to the potential direct effects of sleep on weight loss, sleep may influence physical activity behavior, which is important for long-term weight loss. It has been hypothesized that there is a bidirectional relationship between sleep and physical activity (46, 47). Engaging in physical activity may help improve nighttime sleep, but better sleep may also promote higher levels of physical activity. High amounts of moderate intensity physical activity (250-300 min/wk) are recommended for weight loss maintenance (7, 48). In this study, participants were recommended to complete ≥300 min/wk of moderate intensity physical activity in bouts of ≥10 minutes, a supervised exercise program was provided for 6 months, and complimentary access to a fitness facility was given for 18 months. We found that later waketimes were associated with reduced odds of meeting the recommended amount of MVPA after adjustment for covariates. It is possible that “sleeping in” reduces the likelihood of engaging in physical activity because it lessens the possibility of exercising in the morning prior to social pressures like work, school, caring for children, etc. We previously reported that weight loss maintainers who engaged in high amounts of weekly MVPA engaged in ~30 min of MVPA within 3 hours of waking up each day suggesting that morning activity may be critical for accumulating the high amounts of physical activity recommended for long-term weight loss (49). We also found that longer sleep durations and time in bed (per hour) reduced the odds of meeting the physical activity recommendation by 33% and 41% after adjustment for covariates, respectively. This suggests that the finite nature of a 24-h day may limit the possibility of engaging in both longer sleep and recommended physical activity. Spending more time in bed may cut into the “free time” which could be used to engage in physical activity. Finally, we found that higher WASO, more awakenings, and higher SOL were associated with reduced odds of meeting the MVPA recommendations in adjusted models. These data align with previous studies showing that sleep quality (50, 51), SOL (52), and sleep efficiency (52, 53) predicted next day physical activity. Collectively, these data suggest that sleep duration and quality may important determinants of physical activity behavior. Future prospective studies are needed to understand what parameters of sleep are important for promoting engagement in physical activity.

Sleep may also influence dietary behaviors during a behavioral weight loss program. Sleep restriction has been shown to influence the brain’s response to food stimuli (54) and contribute to an increase in EI, particularly carbohydrate intake (22). In contrast to these experimental studies, we found only one significant association between sleep and meeting the prescribed calorie-reduced diet. Higher WASO (per 10 minutes) was associated with 10% increased odds of meeting the prescribed calorie-restricted diet; however, this did not remain significant after adjustment for covariates. One limitation of this study is that we utilized self-reported 3-day food records to quantity food intake. These food records are prone to bias and underreporting, particularly in individuals with overweight and obesity (55–58). It is possible that these imprecise measures of EI did not reflect true EI making it difficult to examine the true association between sleep and EI. Future studies may benefit from utilizing more objective measures of EI.

Short sleep may affect body composition changes during weight loss. Two prior studies have shown that experimentally shortened sleep leads to increased lean mass loss compared to obtaining sufficient sleep during caloric restriction (23, 59). This increased loss of lean mass may be considered unhealthy weight loss. In the current study, no sleep variables were associated with change in lean mass. It is possible that the provision of supervised exercise and engagement in high amounts of MVPA helped to preserve lean mass as has been shown previously (60, 61). Future experimental studies are needed to understand whether the provision of supervised exercise and MVPA is sufficient to preserve lean mass during periods of insufficient sleep and caloric restriction.

There are several limitations to our study. First, this was a secondary data analysis, and the original study was not designed or powered examine the association between indices of sleep duration, timing, and quality with dietary adherence, physical activity, and weight loss. Few participants in this study had reported sleep disturbances; thus, the range for indices of sleep quantity and quality may have been limited. However, at baseline the mean sleep efficiency was 83.3 ± 6.8% and mean sleep duration was 411.0 ± 68.2 min, suggesting that this sample included participants with a range of different sleep characteristics, including individuals with disturbed sleep. Further, the participants of this study were predominantly White, Non-Hispanic, and female. Thus, the findings from this study may not be generalizable to other populations. This study utilized the SWA to measure indices of sleep timing, duration, and quality. The SWA has been validated against polysomnography and wrist actigraphy for measuring indices of sleep; however, as with any device it has inherent limitations when measuring sleep duration and indices of sleep quality. Specifically, wearable devices are prone to misclassification of motionless wake and periods of sleep that are accompanied by movement. Studies typically utilize complimentary sleep diary information to score wearable sleep data; however, because sleep was not an *a-priori* variable of interest, this study did not obtain sleep diaries to assist with sleep scoring. This could have resulted in misclassification of certain sleep parameters, particularly SOL which was calculated by estimating when a person began attempting sleep. In addition, some indices of sleep were highly correlated with one another (Supplemental Tables 4–7); thus, it is not surprising that these sleep that were highly correlated resulted in similar Beta estimates in our models. This study did not capture other dimensions of sleep health (e.g., sleep apnea, subjective sleep quality, daytime sleepiness, etc.) that may be important for body weight regulation. Further, given the study population (i.e., adults with overweight and obesity), it is likely that a significant number of participants in this study had undiagnosed sleep apnea which may have confounded our results. Finally, it is important to recognize that this study was not designed to determine causality; thus, it is unclear if better sleep helps to improve weight loss or whether having greater weight loss leads to improvements in sleep.

In summary, we found that several components of sleep were associated with weight loss and adherence to physical activity and dietary recommendations during an 18-month behavioral weight loss intervention. Greater sleep efficiency was associated with greater weight loss after adjustment for relevant covariates including EI and MVPA. Aspects of both sleep quantity and sleep quality were associated with adherence to MVPA recommendations suggesting that several components of sleep may be important in achieving the high amounts of MVPA necessary for long-term weight loss. Indices of sleep were not associated with self-reported adherence to the dietary recommendations after adjusting for covariates. Collectively, these findings suggest that sleep health, particularly aspects of sleep continuity, may influence the effectiveness of behavioral interventions aimed at reducing body weight. Future studies are needed to determine if improving sleep health during a behavioral weight loss intervention is feasible and enhances weight loss.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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DATA AVAILABILITY

Deidentified participant data are available upon request. A written request, including hypotheses, methodology, and a statistical analysis plan, should be directed to Dr. Victoria Catenacci (vicki.catenacci@cuanschutz.edu).

REFERENCES

1. Hales CM, Carroll MD, Fryar CD, Ogden CL. Prevalence of Obesity and Severe Obesity Among Adults: United States, 2017-2018. NCHS Data Brief. 2020(360):1–8.
2. Poirier P, Giles TD, Bray GA, Hong Y, Stern JS, Pi-Sunyer FX, et al. Obesity and cardiovascular disease: pathophysiology, evaluation, and effect of weight loss an update of the 1997 American Heart Association Scientific statement on obesity and heart disease from the obesity committee of the council on nutrition, physical activity, and metabolism. Circulation. 2006;113(6):898–918. [PubMed: 16380542]
3. Hubert HB, Feinleib M, McNamara PM, Castelli WP. Obesity as an independent risk factor for cardiovascular disease: a 26-year follow-up of participants in the Framingham Heart Study. Circulation. 1983;67(5):968–77. [PubMed: 6219830]
4. Mokdad AH, Ford ES, Bowman BA, Dietz WH, Vinicor F, Bales VS, et al. Prevalence of obesity, diabetes, and obesity-related health risk factors, 2001. JAMA. 2003;289(1):76–9. [PubMed: 12503980]
5. Chen Y, Wang X, Wang J, Yan Z, Luo J. Excess body weight and the risk of primary liver cancer: an updated meta-analysis of prospective studies. Eur J Cancer. 2012;48(14):2137–45. [PubMed: 22446023]
6. Sanfilippo KM, McTigue KM, Fidler CJ, Neaton JD, Chang Y, Fried LF, et al. Hypertension and obesity and the risk of kidney cancer in 2 large cohorts of US men and women. Hypertension. 2014;63(5):934–41. [PubMed: 24637660]
7. Jensen MD, Ryan DH, Apovian CM, Ard JD, Comuzzie AG, Donato KA, et al. 2013 AHA/ACC/TOS guideline for the management of overweight and obesity in adults: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and The Obesity Society. J Am Coll Cardiol. 2014;63(25 Pt B):2985–3023. [PubMed: 24239920]
8. Wadden TA. Treatment of obesity by moderate and severe caloric restriction. Results of clinical research trials. Ann Intern Med. 1993;119(7 Pt 2):688–93. [PubMed: 8363198]
9. Ayyad C, Andersen T. Long-term efficacy of dietary treatment of obesity: a systematic review of studies published between 1931 and 1999. Obes Rev. 2000;1(2):113–9. [PubMed: 12119984]
10. Kraemer WJ, Volek JS, Clark KL, Gordon SE, Puhl SM, Koziris LP, et al. Influence of exercise training on physiological and performance changes with weight loss in men. Med Sci Sports Exerc. 1999;31(9):1320–9. [PubMed: 10487375]
11. Wing RR, Phelan S. Long-term weight loss maintenance. Am J Clin Nutr. 2005;82(1):222S–5S. [PubMed: 16002825]
12. Anderson JW, Konz EC, Frederich RC, Wood CL. Long-term weight-loss maintenance: a meta-analysis of US studies. Am J Clin Nutr. 2001;74(5):579–84. [PubMed: 11684524]
13. St-Onge MP. Sleep-obesity relation: underlying mechanisms and consequences for treatment. Obes Rev. 2017;18 Suppl 1:34–9. [PubMed: 28164452]
14. Ogilvie RP, Patel SR. The epidemiology of sleep and obesity. Sleep health. 2017;3(5):383–8. [PubMed: 28923198]
15. Patel SR, Hu FB. Short sleep duration and weight gain: a systematic review. Obesity (Silver Spring, Md). 2008;16(3):643–53. [PubMed: 18239586]
16. Wu Y, Zhai L, Zhang D. Sleep duration and obesity among adults: a meta-analysis of prospective studies. Sleep Med. 2014;15(12):1456–62. [PubMed: 25450058]
17. Sun W, Yuan J, Yu Y, Wang Z, Shankar N, Ali G, et al. Poor sleep quality associated with obesity in men. Sleep & breathing = Schlaf & Atmung. 2016;20(2):873–80. [PubMed: 25957618]
18. Wirth MD, Hébert JR, Hand GA, Youngstedt SD, Hurley TG, Shook RP, et al. Association between actigraphic sleep metrics and body composition. Ann Epidemiol. 2015;25(10):773–8. [PubMed: 26071309]
19. Sa J, Choe S, Cho BY, Chaput JP, Kim G, Park CH, et al. Relationship between sleep and obesity among U.S. and South Korean college students. BMC Public Health. 2020;20(1):96. [PubMed: 31969131]

20. Park SK, Jung JY, Oh CM, McIntyre RS, Lee JH. Association Between Sleep Duration, Quality and Body Mass Index in the Korean Population. J Clin Sleep Med. 2018;14(8):1353–60. [PubMed: 30092896]
21. Logue EE, Scott ED, Palmieri PA, Dudley P. Sleep duration, quality, or stability and obesity in an urban family medicine center. J Clin Sleep Med. 2014;10(2):177–82. [PubMed: 24533001]
22. Markwald RR, Melanson EL, Smith MR, Higgins J, Perreault L, Eckel RH, et al. Impact of insufficient sleep on total daily energy expenditure, food intake, and weight gain. Proc Natl Acad Sci U S A. 2013;110(14):5695–700. [PubMed: 23479616]
23. Nedeltcheva AV, Kilkus JM, Imperial J, Schoeller DA, Penev PD. Insufficient sleep undermines dietary efforts to reduce adiposity. Ann Intern Med. 2010;153(7):435–41. [PubMed: 20921542]
24. Sawamoto R, Nozaki T, Furukawa T, Tanahashi T, Morita C, Hata T, et al. Higher sleep fragmentation predicts a lower magnitude of weight loss in overweight and obese women participating in a weight-loss intervention. Nutr Diabetes. 2014;4(10):e144. [PubMed: 25347608]
25. Thomson CA, Morrow KL, Flatt SW, Wertheim BC, Perfect MM, Ravia JJ, et al. Relationship between sleep quality and quantity and weight loss in women participating in a weight-loss intervention trial. Obesity (Silver Spring, Md). 2012;20(7):1419–25. [PubMed: 22402738]
26. Chaput JP, Tremblay A. Sleeping habits predict the magnitude of fat loss in adults exposed to moderate caloric restriction. Obes Facts. 2012;5(4):561–6. [PubMed: 22854682]
27. Papandreou C, Bulló M, Díaz-López A, Martínez-González MA, Corella D, Castañer O, et al. High sleep variability predicts a blunted weight loss response and short sleep duration a reduced decrease in waist circumference in the PREDIMED-Plus Trial. Int J Obes (Lond). 2020;44(2):330–9. [PubMed: 31217539]
28. Kline CE, Chasens ER, Bizhanova Z, Sereika SM, Buysse DJ, Imes CC, et al. The association between sleep health and weight change during a 12-month behavioral weight loss intervention. Int J Obes (Lond). 2021;45(3):639–49. [PubMed: 33414489]
29. O'Brien EM, Fava J, Subak LL, Stone K, Hart CN, Demos K, et al. Sleep duration and weight loss among overweight/obese women enrolled in a behavioral weight loss program. Nutr Diabetes. 2012;2(9):e43. [PubMed: 23446658]
30. Chang MW, Tan A, Schaffir J, Wegener DT. Sleep and weight loss in low-income overweight or obese postpartum women. BMC Obes. 2019;6:12. [PubMed: 30984405]
31. Tuomilehto H, Peltonen M, Partinen M, Lavigne G, Eriksson JG, Herder C, et al. Sleep duration, lifestyle intervention, and incidence of type 2 diabetes in impaired glucose tolerance: The Finnish Diabetes Prevention Study. Diabetes Care. 2009;32(11):1965–71. [PubMed: 19651919]
32. Kline CE, Burke LE, Sereika SM, Imes CC, Rockette-Wagner B, Mendez DD, et al. Bidirectional Relationships Between Weight Change and Sleep Apnea in a Behavioral Weight Loss Intervention. Mayo Clin Proc. 2018;93(9):1290–8. [PubMed: 30082081]
33. Fenton S, Burrows TL, Collins CE, Holliday EG, Kolt GS, Murawski B, et al. Behavioural mediators of reduced energy intake in a physical activity, diet, and sleep behaviour weight loss intervention in adults. Appetite. 2021;165:105273. [PubMed: 33945842]
34. Fenton S, Burrows TL, Collins CE, Rayward AT, Murawski B, Duncan MJ. Efficacy of a Multi-Component m-Health Diet, Physical Activity, and Sleep Intervention on Dietary Intake in Adults with Overweight and Obesity: A Randomised Controlled Trial. Nutrients. 2021;13(7).
35. Catenacci VA, Ostendorf DM, Pan Z, Bing K, Wayland LT, Seyoum E, et al. The Impact of Timing of Exercise Initiation on Weight Loss: An 18-Month Randomized Clinical Trial. Obesity (Silver Spring, Md). 2019;27(11):1828–38. [PubMed: 31565869]
36. Mifflin MD, St Jeor ST, Hill LA, Scott BJ, Daugherty SA, Koh YO. A new predictive equation for resting energy expenditure in healthy individuals. Am J Clin Nutr. 1990;51(2):241–7. [PubMed: 2305711]
37. Jakicic JM, Marcus M, Gallagher KI, Randall C, Thomas E, Goss FL, et al. Evaluation of the SenseWear Pro Armband to Assess Energy Expenditure during Exercise. Med Sci Sports Exerc. 2004;36(5):897–904. [PubMed: 15126727]
38. Brazeau AS, Karelis AD, Mignault D, Lacroix MJ, Prud'homme D, Rabasa-Lhoret R. Test-retest reliability of a portable monitor to assess energy expenditure. Appl Physiol Nutr Metab. 2011;36(3):339–43. [PubMed: 21574780]

39. Fruin ML, Rankin JW. Validity of a multi-sensor armband in estimating rest and exercise energy expenditure. Med Sci Sports Exerc. 2004;36(6):1063–9. [PubMed: 15179178]
40. Kölling S, Endler S, Ferrauti A, Meyer T, Kellmann M. Comparing Subjective With Objective Sleep Parameters Via Multisensory Actigraphy in German Physical Education Students. Behav Sleep Med. 2016;14(4):389–405. [PubMed: 26372692]
41. Shin M, Swan P, Chow CM. The validity of Actiwatch2 and SenseWear armband compared against polysomnography at different ambient temperature conditions. Sleep Sci. 2015;8(1):9–15. [PubMed: 26483937]
42. Grau L, Arbet J, Ostendorf DM, Blankenship JM, Panter SL, Catenacci VA, et al. Using an Algorithm to Identify Indices of Sleep Quantity and Quality from a Wearable Armband. Sleep Science. Accepted for publication 12/23/21.
43. Liu W, Zhang R, Tan A, Ye B, Zhang X, Wang Y, et al. Long sleep duration predicts a higher risk of obesity in adults: a meta-analysis of prospective cohort studies. J Public Health (Oxf). 2019;41(2):e158–e68. [PubMed: 30107483]
44. Elder CR, Gullion CM, Funk KL, Debar LL, Lindberg NM, Stevens VJ. Impact of sleep, screen time, depression and stress on weight change in the intensive weight loss phase of the LIFE study. Int J Obes (Lond). 2012;36(1):86–92. [PubMed: 21448129]
45. Alfaris N, Wadden TA, Sarwer DB, Diwald L, Volger S, Hong P, et al. Effects of a 2-year behavioral weight loss intervention on sleep and mood in obese individuals treated in primary care practice. Obesity (Silver Spring, Md). 2015;23(3):558–64. [PubMed: 25611944]
46. Kline CE. The bidirectional relationship between exercise and sleep: Implications for exercise adherence and sleep improvement. Am J Lifestyle Med. 2014;8(6):375–9. [PubMed: 25729341]
47. Youngstedt SD, Kline CE. Epidemiology of exercise and sleep. Sleep Biol Rhythms. 2006;4(3):215–21. [PubMed: 25374476]
48. Donnelly JE, Blair SN, Jakicic JM, Manore MM, Rankin JW, Smith BK. American College of Sports Medicine Position Stand. Appropriate physical activity intervention strategies for weight loss and prevention of weight regain for adults. Med Sci Sports Exerc. 2009;41(2):459–71. [PubMed: 19127177]
49. Creasy SA, Hibbing PR, Cotton E, Lyden K, Ostendorf DM, Willis EA, et al. Temporal patterns of physical activity in successful weight loss maintainers. Int J Obes (Lond). 2021.
50. Dzierzewski JM, Buman MP, Giacobbi PR Jr., Roberts BL, Aiken-Morgan AT, Marsiske M, et al. Exercise and sleep in community-dwelling older adults: evidence for a reciprocal relationship. J Sleep Res. 2014;23(1):61–8. [PubMed: 23980920]
51. Tang NK, Sanborn AN. Better quality sleep promotes daytime physical activity in patients with chronic pain? A multilevel analysis of the within-person relationship. PLoS One. 2014;9(3):e92158. [PubMed: 24667276]
52. Baron KG, Reid KJ, Zee PC. Exercise to improve sleep in insomnia: exploration of the bidirectional effects. J Clin Sleep Med. 2013;9(8):819–24. [PubMed: 23946713]
53. Lambiase MJ, Thurston RC. Physical activity and sleep among midlife women with vasomotor symptoms. Menopause. 2013;20(9):946–52. [PubMed: 23531686]
54. St-Onge MP, McReynolds A, Trivedi ZB, Roberts AL, Sy M, Hirsch J. Sleep restriction leads to increased activation of brain regions sensitive to food stimuli. Am J Clin Nutr. 2012;95(4):818–24. [PubMed: 22357722]
55. Dahle JH, Ostendorf DM, Zaman A, Pan Z, Melanson EL, Catenacci VA. Underreporting of energy intake in weight loss maintainers. Am J Clin Nutr. 2021.
56. Dhurandhar NV, Schoeller D, Brown AW, Heymsfield SB, Thomas D, Sørensen TI, et al. Energy balance measurement: when something is not better than nothing. Int J Obes (Lond). 2015;39(7):1109–13. [PubMed: 25394308]
57. Hill RJ, Davies PS. The validity of self-reported energy intake as determined using the doubly labelled water technique. Br J Nutr. 2001;85(4):415–30. [PubMed: 11348556]
58. Lichtman SW, Pisarska K, Berman ER, Pestone M, Dowling H, Offenbacher E, et al. Discrepancy between self-reported and actual caloric intake and exercise in obese subjects. N Engl J Med. 1992;327(27):1893–8. [PubMed: 1454084]

59. Wang X, Sparks JR, Bowyer KP, Youngstedt SD. Influence of sleep restriction on weight loss outcomes associated with caloric restriction. Sleep. 2018;41(5).

60. Ross R, Dagnone D, Jones PJ, Smith H, Paddags A, Hudson R, et al. Reduction in obesity and related comorbid conditions after diet-induced weight loss or exercise-induced weight loss in men: a randomized, controlled trial. Ann Intern Med. 2000;133(2):92–103. [PubMed: 10896648]

61. Weiss EP, Racette SB, Villareal DT, Fontana L, Steger-May K, Schechtman KB, et al. Lower extremity muscle size and strength and aerobic capacity decrease with caloric restriction but not with exercise-induced weight loss. Journal of applied physiology (Bethesda, Md : 1985). 2007;102(2):634–40. [PubMed: 17095635]

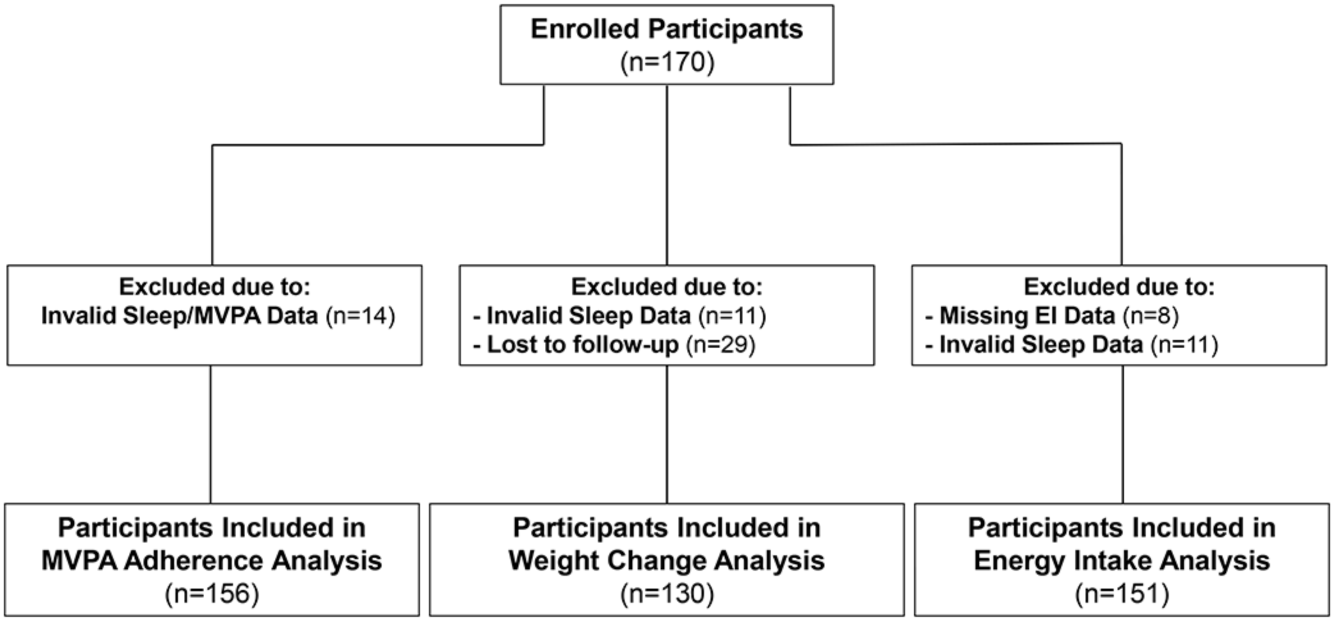

FIGURE 1.
Study Enrollment and Inclusion in Analyses

Table 1.

Baseline Characteristics (n=156)

	Mean ± SD or n, (%)
Age (years)	39.7 ± 9.2
Sex	
Female	131, 84%
Male	25, 16%
Race	
White	122, 78%
Black	22, 14%
Other	12, 8%
Ethnicity	
Hispanic or Latino	40, 26%
Non-Hispanic or Latino	116, 74%
BMI (kg/m^2)	34.4 ± 4.2
Weight (kg)	95.4 ± 15.4
Energy Intake (kcal/d)	1805 ± 505
MVPA (min/d)	23.9 ± 25.1
Bedtime (hh:mm)	22:43 ± 01:06
Mid-point of sleep (hh:mm)	03:08 ± 01:11
Waketime (hh:mm)	07:11 ± 01:16
Regularity (min)	75.4 ± 38.1
Sleep duration (min/d)	411 ± 68
Time in bed (min/d)	493 ± 70

	Mean ± SD or n, (%)
SOL (min/d)	14.1 ± 7.5
WASO (min/d)	69.5 ± 41.1
Awakenings (events)	18 ± 9
Sleep efficiency (%)	83.4 ± 6.8

BMI- body mass index; SOL- sleep onset latency; WASO- wake after sleep onset; Regularity was defined as the standard deviation of waketime

Table 2.

Association between Indices of Sleep and Weight Change

	Model 1 (n=130)			Model 2 n=130)			Model 3 (n=123)		
	B Estimate	**(95% CI)**	**p-value**	**B Estimate**	**(95% CI)**	**p-value**	**B Estimate**	**(95% CI)**	**p-value**
Bedtime (hh:mm)	−0.42	(−1.01, 0.18)	0.17	−0.47	(−1.07, 0.13)	0.13	−0.45	(−1.08, 0.17)	0.15
Midpoint of sleep (hh:mm)	−0.32	(−0.78, 0.13)	0.16	−0.33	(−0.79, 0.12)	0.15	−0.35	(−0.86, 0.16)	0.18
Waketime (hh:mm)	−0.28	(−0.85, 0.29)	0.33	−0.23	(−0.81, 0.35)	0.43	−0.33	(−0.94, 0.27)	0.28
Regularity (per 10 minutes)	0.06	(−0.06, 0.18)	0.34	0.06	(−0.07, 0.18)	0.39	0.08	(−0.05, 0.21)	0.23
Sleep Duration (per hour)	−0.41	(−1.08, 0.26)	0.23	−0.27	(−0.96, 0.42)	0.45	−0.52	(−1.26, 0.22)	0.17
Time in Bed (per hour)	−0.04	(−0.64, 0.55)	0.89	0.07	(−0.53, 0.68)	0.81	−0.11	(−0.76, 0.54)	0.73
SOL (per 10 minutes)	1.13	(0.42, 1.84)	**<.01**	1.17	(0.45, 1.89)	**<.01**	1.01	(0.19, 1.83)	**0.02**
WASO (per 10 minutes)	0.11	(−0.05, 0.27)	0.17	0.11	(−0.05, 0.27)	0.17	0.12	(−0.05, 0.29)	0.17
WASO (per 10 minutes)	−0.18	(−0.50, 0.14)	0.26	−0.18	(−0.50, 0.13)	0.25	−0.17	(−0.51, 0.17)	0.32
Month	−0.12	(−0.28, 0.05)	0.16	−0.12	(−0.28, 0.05)	0.16	−0.13	(−0.30, 0.05)	0.17
WASO*Month	0.02	(0.00, 0.05)	**0.04**	0.02	(0.00, 0.05)	**0.03**	0.02	(−0.00, 0.05)	0.05
Awakenings (per 5 events)	0.13	(−0.22, 0.48)	0.47	0.15	(−0.21, 0.50)	0.41	0.17	(−0.21, 0.55)	0.38
Awakenings (per 5 events)	−0.78	(−1.48, −0.07)	**0.03**	−0.76	(−1.46, −0.05)	**0.04**	−0.68	(−1.43, 0.07)	0.08
Month	−0.23	(−0.42, −0.03)	**0.02**	−0.23	(−0.42, −0.03)	**0.03**	−0.22	(−0.42, −0.01)	**0.04**
Awakenings*Month	0.08	(0.03, 0.13)	**<.01**	0.08	(0.03, 0.13)	**<.01**	0.07	(0.02, 0.13)	**0.01**
Sleep Efficiency (per 5%)	−0.60	(−1.12, −0.08)	**0.02**	−0.57	(−1.10, −0.03)	**0.04**	−0.60	(−1.17, −0.03)	**0.04**

Each measure of sleep was included as a predictor of weight (kg), adjusting for baseline weight. Model 1 included the measure of sleep, time, and baseline weight; Model 2 added age, BMI, race, ethnicity, completer, and intervention arm to Model 1; Model 3 added EI (kcal/d) and MVPA (min/wk) to Model 2. WASO- wake after sleep onset; SOL- sleep onset latency; Regularity was defined as the standard deviation of waketime

Table 3.

Association between Indices of Sleep and Adherence to MVPA Recommendation

	Model 1 (n=156)				**Model 2 (n=156)**			
	Odds Ratio	**(95% CI)**	**p-value**	**FDR p-value**	**Odds Ratio**	**(95% CI)**	**p-value**	**FDR p-value**
Bedtime (per hour)	1.09	(0.86, 1.37)	0.48	0.53	1.04	(0.81, 1.34)	0.73	0.73
Midpoint of sleep (per hour)	0.87	(0.70, 1.08)	0.21	0.29	0.84	(0.66, 1.06)	0.14	0.20
Waketime (per hour)	0.80	(0.64, 0.99)	**0.04**	0.07	0.68	(0.52, 0.88)	**<0.01**	**0.01**
Regularity (per 10 minutes)	0.98	(0.93, 1.04)	0.59	0.59	0.98	(0.92, 1.04)	0.46	0.52
Sleep Duration (per hour)	0.75	(0.58, 0.98)	**0.03**	0.07	0.67	(0.50, 0.90)	**<0.01**	**0.02**
Time in Bed (per hour)	0.69	(0.54, 0.88)	**<0.01**	**0.03**	0.59	(0.44, 0.78)	**<0.001**	**<0.01**
SOL (per 10 minutes)	0.57	(0.38, 0.84)	**<0.01**	**0.03**	0.53	(0.34, 0.82)	**<0.01**	**0.01**
WASO (per 10 minutes)	0.92	(0.85, 1.00)	**0.04**	0.07	0.90	(0.82, 0.98)	**0.01**	**0.02**
Awakenings (per 5 events)	0.81	(0.68, 0.96)	**0.02**	0.06	0.75	(0.62, 0.91)	**<0.01**	**0.01**
Sleep Efficiency (per 5%)	1.14	(0.91, 1.41)	0.25	0.32	1.17	(0.92, 1.49)	0.19	0.24

Each measure of sleep was included as a predictor of adherence to the MVPA recommendation (≥300 min/wk). Model 1 included the measure of sleep and time; Model 2 added age, BMI, sex, race, ethnicity, completer, and intervention arm to Model 1. WASO- wake after sleep onset; SOL- sleep onset latency; regularity was defined as the standard deviation of waketime

Table 4.

Association between Indices of Sleep and Adherence to EI Recommendation

	Model 1 (n=151)				Model 2 (n=151)			
	Odds Ratio	**(95% CI)**	**p-value**	**FDR p-value**	**Odds Ratio**	**(95% CI)**	**p-value**	**FDR p-value**
Bedtime (per hour)	1.07	(0.88, 1.31)	0.48	0.68	1.07	(0.87, 1.31)	0.51	0.76
Midpoint of sleep (per hour)	1.04	(0.87, 1.25)	0.66	0.74	1.02	(0.85, 1.22)	0.85	0.95
Waketime (per hour)	1.17	(0.98, 1.40)	0.08	0.20	1.12	(0.93, 1.34)	0.23	0.58
Regularity (per 10 minutes)	1.03	(0.98, 1.09)	0.21	0.42	1.01	(0.96, 1.07)	0.61	0.76
Sleep Duration (per hour)	0.92	(0.74, 1.14)	0.44	0.68	0.90	(0.72, 1.13)	0.35	0.71
Time in Bed (per hour)	1.04	(0.86, 1.27)	0.67	0.74	1.00	(0.82, 1.23)	0.98	0.98
SOL (per 10 minutes)	1.03	(0.77, 1.39)	0.82	0.82	0.91	(0.67, 1.24)	0.56	0.76
WASO (per 10 minutes)	1.10	(1.03, 1.16)	**<0.01**	**0.03**	1.09	(1.02, 1.16)	**<0.01**	0.08
Awakenings (per 5 events)	1.17	(1.02, 1.33)	**0.02**	0.07	1.14	(1.00, 1.30)	0.06	0.19
Sleep Efficiency (per 5%)	0.80	(0.67, 0.96)	**0.02**	0.07	0.83	(0.68, 1.01)	0.06	0.19

Each measure of sleep was included as a predictor of adherence to the dietary recommendation (1200-1800 kcal/d). Model 1 included the measure of sleep and time; Model 2 added age, BMI, sex, race, ethnicity, completer, and intervention arm to Model 1. WASO- wake after sleep onset; SOL- sleep onset latency; regularity was defined as the standard deviation of waketime