Objective Sleep Characteristics and Cardiometabolic Health in Young Adolescents

Elizabeth M. Cespedes Feliciano, ScD, MSc,[a] Mirja Quante, MD,[b,c] Sheryl L. Rifas-Shiman, MPH,[d] Susan Redline, MD,[b] Emily Oken, MD, MPH,[d] Elsie M. Taveras, MD, MPH[e,f]

abstract

BACKGROUND AND OBJECTIVES: Shorter sleep duration is associated with childhood obesity. Few studies measure sleep quantity and quality objectively or examine cardiometabolic biomarkers other than obesity.

METHODS: This cross-sectional study of 829 adolescents derived sleep duration, efficiency and moderate-to-vigorous physical activity from >5 days of wrist actigraphy recording for >10 hours/day. The main outcome was a metabolic risk score (mean of 5 sex-specific z-scores for waist circumference, systolic blood pressure, high-density lipoprotein cholesterol scaled inversely, and log-transformed triglycerides and homeostatic model assessment of insulin resistance), for which higher scores indicate greater metabolic risk. Secondary outcomes included score components and dual-energy radiograph absorptiometry fat mass. We measured socioeconomic status, race and/or ethnicity, pubertal status, and obesity-related behaviors (television-viewing and fast food and sugar-sweetened beverage consumption) using questionnaires.

RESULTS: The sample was 51.5% girls; mean (SD) age 13.2 (0.9) years, median (interquartile range) sleep duration was 441.1 (54.8) minutes per day and sleep efficiency was 84.0% (6.3). Longer sleep duration was associated with lower metabolic risk scores (−0.11 points; 95% CI: −0.19 to −0.02, per interquartile range). Associations with sleep efficiency were similar and persisted after adjustment for BMI *z* score and physical activity, television-viewing, and diet quality. Longer sleep duration and greater sleep efficiency were also favorably associated with waist circumference, systolic blood pressure, high-density lipoprotein cholesterol, and fat mass.

CONCLUSIONS: Longer sleep duration and higher sleep efficiency were associated with a more favorable cardiometabolic profile in early adolescence, independent of other obesity-related behaviors. These results support the need to assess the role of sleep quantity and quality interventions as strategies for improving cardiovascular risk profiles of adolescents.

[a]Division of Research, Kaiser Permanente Northern California, Oakland, California; [b]Division of Sleep and Circadian Disorders, Department of Medicine, Brigham and Women's Hospital and Beth Israel Deaconess Medical Center, [d]Division of Chronic Disease Research Across the Lifecourse, Department of Population Medicine, Harvard Pilgrim Health Care Institute, Harvard Medical School, and [e]Department of Nutrition, Harvard T. H. Chan School of Public Health, Harvard University, Boston, Massachusetts; [c]Department of Neonatology, University of Tübingen, Tübingen, Germany; and [f]Division of General Academic Pediatrics, Massachusetts General Hospital for Children, Boston, Massachusetts

Dr Cespedes Feliciano conceptualized and designed the study and wrote the initial draft of the manuscript and subsequent revisions; Dr Quante conceptualized and designed the study; Drs Taveras and Redline obtained funding for the study and conceptualized and designed the study; Dr Oken obtained funding for the study and oversaw data collection; Ms Rifas-Shiman conducted

WHAT'S KNOWN ON THIS SUBJECT: Current evidence, composed primarily of cross-sectional studies with self-reported sleep duration, suggests that short sleep increases childhood obesity risk. Limited evidence, mainly in adults, links poor sleep quality, including sleep fragmentation, and increased variability in sleep duration, to cardiometabolic risk.

WHAT THIS STUDY ADDS: Longer sleep duration and higher sleep efficiency (measured by using actigraphy) are associated with a more favorable cardiometabolic profile, including lower abdominal adiposity, lower systolic blood pressure, and higher high-density lipoprotein cholesterol. Many associations were independent of obesity-related behaviors and BMI.

To cite: Cespedes Feliciano EM, Quante M, Rifas-Shiman SL, et al. Objective Sleep Characteristics and Cardiometabolic Health in Young Adolescents. *Pediatrics*. 2018;142(1): e20174085

Obesity and cardiovascular risk factors in childhood promote cardiovascular disease later in life.[1–3] Sleep has emerged as a potential target for obesity prevention: in accumulating evidence, including in our previous work, authors have observed that shorter childhood sleep duration leads to higher BMI.[4–7] However, authors of few studies examine whether child or adolescent sleep duration is associated with other aspects of cardiometabolic risk (eg, blood pressure, blood lipids, and insulin resistance),[8] and fewer yet examine the contribution of sleep quality (eg, efficiency) to cardiometabolic risk.[9,10] In addition, authors of most studies used subjectively reported sleep characteristics. Studies in which authors used objective measurements (eg, polysomnography[11–17] or actigraphy[18–27]) often had small sample sizes or had no control for confounders, such as socioeconomic status, or potential mediators, such as physical activity, television viewing, or diet quality.

With the current study, we fill these gaps by examining actigraphy-estimated sleep characteristics with cardiometabolic health in a large sample of children entering adolescence, a period with dramatic changes in sleep architecture and duration, high prevalence of inadequate sleep,[28] and emerging cardiovascular risk profiles.[1–3,29] In this cross-sectional study, we examine associations of sleep quantity and quality with a comprehensive range of measurements of adiposity and cardiometabolic risk factors including blood pressure, lipids, and insulin resistance.[30]

METHODS

Study Participants

Project Viva recruited pregnant women from their initial prenatal visit at Atrius Health in eastern Massachusetts (1999–2002) and has followed mother-child pairs since. After delivery, mothers reported their child's race and/or ethnicity. Of the 2128 children enrolled, 1038 participated in the adolescent in-person visit (mean [SD] age was 13.2 [0.9] years; range: 11.9–16.6 years) and were eligible for the sleep examination. Of these, 829 provided valid actigraphy measurements. A smaller number completed blood draws and dual-energy radiograph absorptiometry (DXA) scans; sample sizes for each outcome are in Table 1. Women provided written informed consent at each visit, and children began providing verbal consent at midchildhood. All procedures were approved by the relevant institutional review boards.

Actigraphy Protocol and Sleep Exposures

We measured nighttime sleep and daytime physical activity using wrist actigraphy (Actigraph GT3×+) analyzed by using ActiLife-6 software (ActiGraph, Inc, Pensacola, FL). Actigraphs were used to collect activity data in 60-second epochs. We asked adolescents to wear the device on their nondominant wrist for 7 to 10 consecutive days and nights and complete daily sleep logs. We identified each day's main rest interval as the primary sleep period on the basis of logs and observation of a sharp decrease in activity with subsequent increase. Participants with ≥5 days of recording with ≥10 hours of wear-time were included. If the device was removed for ≥1 hour within the in-bed interval, then the primary sleep period was considered invalid. We applied Cole et al's[31] algorithm to classify sleep and wake periods.

Our sleep exposures were from overnight sleep periods, averaged over all nights of valid recording and are as follows: (1) duration (sleep time in minutes) and (2) maintenance efficiency (percentage of time between sleep onset and final awakening spent asleep). Secondary exposures included the following: (3) variability (SD of sleep duration over all valid nights) and (4) wake after sleep onset (WASO) (time awake after sleep onset in minutes).

Adiposity Outcomes

We measured children's height using calibrated stadiometers (Shorr Productions, Olney, MD) and weight with calibrated Tanita scales (model TBF-300A; Tanita Corporation of America, Inc, Arlington Heights, IL). We calculated BMI and age- and sex-specific *z* scores using national reference data.[32,33] We measured total body fat and trunk fat using DXA and calculated fat mass indices (kg/m^2). We measured waist circumference (cm) using a Lefkin woven tape and subscapular and triceps skinfold thicknesses (mm) using Holtain calipers (Holtain LTD, Crosswell, UK) and calculated their sum. Trained research assistants performed all measurements following standardized techniques.[34]

Cardiometabolic Biomarkers

We measured systolic blood pressure with a Dinamap Pro-100 (Critikon of General Electric, Inc, Tampa, FL). We obtained 5 measurements 1 minute apart and calculated mean systolic blood pressure.

A phlebotomist collected blood samples, which were stored at −70°C until they were assayed. Plasma fasting insulin was measured by using an electro-chemiluminescence immunoassay on the Roche Modular system, and fasting glucose was measured enzymatically by using Roche Diagnostics reagents.[35,36] We calculated the homeostatic model assessment of insulin resistance (HOMA-IR) (insulin [μU/mL] × glucose [mg/dL]/405). Triglycerides and high-density lipoprotein (HDL) cholesterol were measured enzymatically.

TABLE 1 Parent, Household, and Child Characteristics According to Actigraphy-Estimated Sleep Duration in Early Adolescence

Characteristics	Overall, *n* = 829	<480 min per d, *n* = 692	≥480 min per d, *n* = 137
Mother and/or household characteristics, mean (SD)			
Maternal age at enrollment, y	32.3 (5.0)	32.3 (5.1)	32.6 (4.7)
Mother graduated college, *n* (%)			
No	228 (27.5)	198 (28.7)	30 (21.9)
Yes	600 (72.5)	493 (71.3)	107 (78.1)
Household income >$70 000 per y at early teenager visit, *n* (%)			
No	177 (22.2)	154 (23.1)	23 (17.4)
Yes	622 (77.8)	513 (76.9)	109 (82.6)
Adolescent's characteristics			
Girl, *n* (%)			
No	402 (48.5)	357 (51.6)	45 (32.8)
Yes	427 (51.5)	335 (48.4)	92 (67.2)
Race and/or ethnicity, *n* (%)			
African American	131 (15.8)	117 (16.9)	14 (10.2)
Hispanic	36 (4.3)	33 (4.8)	3 (2.2)
Asian American	22 (2.7)	21 (3.0)	1 (0.7)
White	532 (64.3)	428 (61.9)	104 (75.9)
Other	107 (12.9)	92 (13.3)	15 (10.9)
Season at early adolescent visit, *n* (%)			
Winter	170 (20.5)	140 (20.2)	30 (21.9)
Spring	222 (26.8)	187 (27.0)	35 (25.5)
Summer	275 (33.2)	229 (33.1)	46 (33.6)
Fall	162 (19.5)	136 (19.7)	26 (19.0)
Tanner stage,[a] mean (SD)	3.6 (1.0)	3.6 (1.0)	3.5 (1.1)
Age, y, mean (SD)	13.2 (0.9)	13.2 (0.9)	13.1 (0.8)
Television viewing, h per d, mean (SD)	2.0 (1.4)	2.1 (1.4)	1.7 (1.1)
Fast food intake, servings per wk, mean (SD)	0.7 (1.1)	0.7 (1.1)	0.6 (1.1)
Sugar sweetened beverage intake, servings per d, mean (SD)	0.8 (0.9)	0.8 (0.9)	0.7 (0.7)
BMI *z* score, mean (SD)	0.36 (1.07)	0.41 (1.06)	0.11 (1.07)
Actigraphy measurements, median (IQR)			
Average daily MVPA, min	7.0 (17.0)	7.0 (16.0)	7.0 (16.5)
Average daily sleep duration, min	441.1 (54.8)	432.7 (46.0)	495.8 (21.9)
Average daily sleep efficiency, %	84.0 (6.3)	83.5 (6.1)	86.3 (4.9)
Average daily WASO, min	74.8 (36.2)	75.9 (36.3)	69.2 (33.9)
Day-to-day variability in sleep duration, SD[b]	56.0 (35.4)	55.7 (35.8)	58.5 (34.1)
Adiposity outcomes, mean (SD)			
BMI *z* score, *n* = 827	0.36 (1.07)	0.41 (1.06)	0.11 (1.07)
Waist circumference, cm, *n* = 829	72.8 (11.7)	73.4 (11.9)	69.7 (10.5)
Sum of skinfolds, mm, *n* = 826	28.2 (13.7)	28.6 (14.2)	26.2 (11.2)
DXA fat mass index, kg/m^2, *n* = 619	6.3 (3.1)	6.4 (3.2)	5.9 (2.3)
DXA trunk fat mass index, kg/m^2, *n* = 619	2.4 (1.5)	2.4 (1.5)	2.2 (1.1)
Cardiometabolic outcomes, mean (SD)			
Metabolic risk, *z* score,[c] *n* = 493	−0.02 (0.60)	0.00 (0.61)	−0.12 (0.56)
HOMA-IR, *n* = 496	3.1 (1.9)	3.2 (2.0)	2.8 (1.4)
Insulin, μU/mL, *n* = 560	15.9 (14.9)	16.4 (15.9)	12.9 (6.1)
Glucose, mg/dL, *n* = 513	92.7 (23.5)	93.0 (25.1)	91.1 (11.5)
Systolic BP, mm Hg, *n* = 823	107.2 (8.9)	107.7 (8.9)	104.9 (9.0)
Triglycerides, mg/dL, *n* = 559	69.8 (31.3)	69.1 (31.3)	73.4 (31.3)
HDL cholesterol, mg/dL, *n* = 560	55.3 (13.1)	55.1 (13.2)	56.9 (12.5)

Data from 829 participants from Project Viva. BP, blood pressure.

[a] Tanner stage pubic hair (5-point scale).

[b] SD of daily time spent asleep (all days), minutes.

[c] Mean of 5 sex- and cohort-specific *z* scores for waist circumference, systolic blood pressure, HDL cholesterol scaled inversely, and log-transformed triglycerides and HOMA-IR; higher scores are indicative of greater metabolic risk.

We derived a metabolic risk score, described previously,[37] as the mean of sex- and cohort-specific *z* scores for waist circumference, systolic blood pressure, HDL cholesterol (scaled inversely), log-transformed HOMA-IR, and log-transformed triglycerides. Higher scores were indicative of greater metabolic risk. Although there is no consistent definition of the metabolic syndrome in children, researchers of previous work have used similar scores.[38–40]

Other Measures

We derived moderate-to-vigorous physical activity (MVPA) from

actigraphy. From total activity (vertical axis counts per minutes) excluding sleep and non–wear-time, we applied Chandler's cut points to derive average MVPA minutes per day.[41] We defined the season of measurement as "Spring" being from March 1 to May 31, "Summer" from June 1 to August 31, "Autumn" from September 1 to November 30, or "Winter" from December 1 to February 28. Via questionnaire, mothers reported their educational attainment and household incomes, and adolescents reported their pubertal status (Tanner stage was derived from a validated 5-point rating scale on pubic hair growth, with higher values indicative of greater pubertal development),[42] the number of hours per day on weekdays and weekends spent watching television, and the servings of fast food and sugar-sweetened beverages consumed per day.

Statistical Analysis

We performed all analyses using SAS version 9.4 (SAS Institute, Inc, Cary, NC). We examined correlations among the sleep exposures and the normality of biomarker measurements. For comparability, we reported associations per interquartile range (IQR) of sleep exposures. Our multivariable linear regression models adjusted for confounding variables selected a priori from previous literature; all models included demographics (adolescents' age, sex, and race and/or ethnicity), socioeconomic status (mothers' education and household income), pubertal status, and season.

To examine the associations of sleep exposures independently of other obesity-related behaviors, we additionally adjusted models for MVPA, television-viewing, and fast food and sugar-sweetened beverages, which authors of previous studies suggest mediate and/or confound the sleep-cardiometabolic risk relationship.[9,10,43–46] Similarly, to examine associations independently of overall adiposity, we adjusted blood biomarker outcomes for BMI *z* score.

To explore whether associations of sleep duration and efficiency were independent, we entered these exposures (Spearman correlation = 0.41) into the same model and reported mutually adjusted results.

We evaluated interactions of sex with sleep exposures through stratified analyses and product terms in multivariable models.

RESULTS

Mean (SD) age was 13.2 (0.9) years, and 51.5% of the sample were girls (Table 1). Median (IQR) sleep duration was 441.1 (54.8) minutes per day, sleep efficiency percentage was 84.0% (6.3), WASO was 74.8 (36.2) minutes, and variability was 56.0 (35.4) minutes. Using actigraphy-estimated sleep duration, a minority (n = 18; 2.2%) of adolescents met the lower bound of the National Sleep Foundation's recommended sleep duration (>480 minutes [8 hours] per day for participants 14–17 years old and >540 minutes [9 hours] per day for participants 11–13 years old).[47] Short sleep (<420 minutes per day) occurred in 31% of the sample (n = 257). A majority were classified as having low sleep efficiency by using the threshold ≤85% (n = 484; 58.4%). Sleep characteristics are reported separately for weekdays and weekend recording in Supplemental Table 3.

Adiposity

Each increment of sleep duration (55 minutes per day) was inversely associated with adiposity, independent of the adjustment for sociodemographics, puberty, and season (Fig 1), including BMI *z* score (−0.15 per IQR; 95% confidence interval [CI]: −0.26 to −0.05), sum of skinfold thicknesses (−2.05 mm; 95% CI: −3.43 to −0.68), DXA fat mass index (−0.52 kg/m^2; 95% CI: −0.89 to −0.15), and DXA trunk fat mass index (−0.26 kg/m^2; 95% CI: −0.43 to −0.08).

Likewise, sleep efficiency (IQR: 6%) was inversely associated with adiposity measured by DXA (Fig 1), including total fat mass index (−0.37 kg/m^2; 95% CI: −0.71 to −0.03) and trunk fat mass index (−0.21 kg/m^2; 95% CI: −0.37 to −0.05).

Sleep variability (IQR: 35 minutes) and WASO (IQR: 36 minutes) had no association with any adiposity measures after multivariable adjustment (Table 2).

Most associations persisted after adjusting for MVPA, television-viewing, and sugar-sweetened beverage and fast food consumption (Table 2, Model 2).

Metabolic Risk Score, Blood Pressure, and Blood Lipids

Longer sleep duration and higher sleep efficiency were associated with lower metabolic risk scores (Fig 2A; −0.11 points per IQR; 95% CI: −0.19 to −0.02 and −0.08 points; 95% CI: −0.16 to −0.01, respectively). Examining the score's individual components, we found these results were driven by a smaller waist circumference (Fig 1E; −2.81 cm; 95% CI: −3.96 to −1.65 and −1.69 cm; 95% CI: −2.78 to −0.61, respectively), lower systolic blood pressure (Fig 2B; −1.36 mm Hg; 95% CI: −2.24 to −0.47 and −1.44 mm Hg; 95% CI: −2.26 to −0.61, respectively), and higher HDL cholesterol (Fig 2C; 1.99 mg/dL; 95% CI: 0.30 to 3.67 and 1.49 mg/dL; 95% CI: −0.04 to 3.02). Associations with the triglyceride and HOMA-IR components were in the expected direction, but CIs were wide (Figs 2D and 2E). Associations of both sleep duration and efficiency with systolic blood pressure and of efficiency with the metabolic risk score and HDL cholesterol persisted with additional adjustment for BMI *z* score and

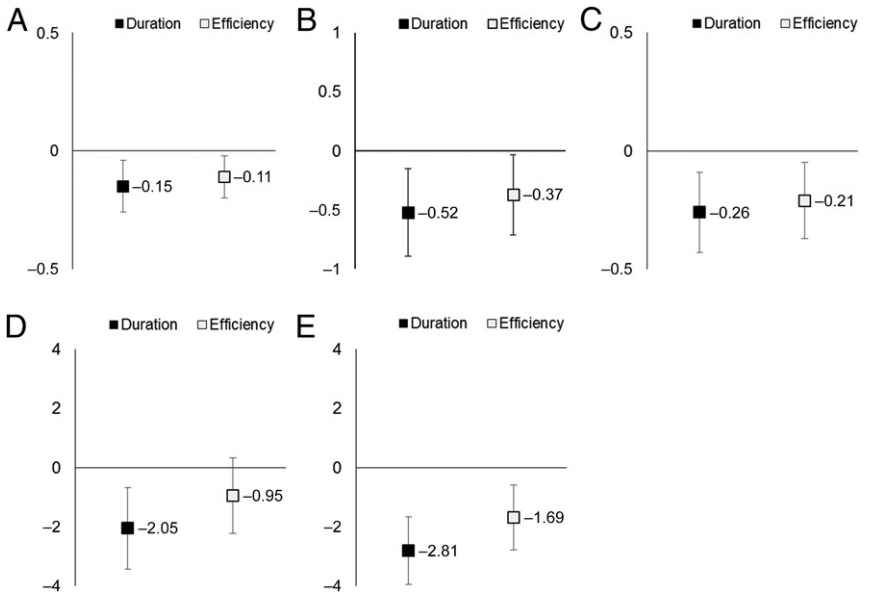

FIGURE 1

Multivariable-adjusted associations of sleep duration and efficiency (per interquartile increase) with adiposity outcomes. Results for adiposity outcomes are shown per IQR of the following sleep exposures: duration (55 minutes) and efficiency (6%). Models adjust for maternal education and household income, season of measurement, and adolescent age, sex, race and/or ethnicity, and puberty (Tanner stage). A, BMI *z* score. B, DXA total fat mass index (in kilograms per meter squared). C, DXA trunk fat index (in kilograms per meter squared). D, Sum of subscapular and triceps skinfolds (millimeters). E, Waist circumference (in centimeters).

MVPA, television-viewing, and diet quality (Table 2).

Sex Differences

The associations of sleep efficiency and WASO with triglycerides and variability with the adiposity measures varied by sex in that there was a robust association in girls that was not found in boys (*P*-interactions < .05; Supplemental Table 4). Otherwise, associations did not vary by sex.

Sleep Quantity Versus Quality

When sleep duration and efficiency were in the same model, each was independently associated with systolic blood pressure. Associations of sleep duration with adiposity (BMI *z* score and waist circumference) and the metabolic risk score were robust to adjustment for sleep efficiency, whereas associations of sleep efficiency with adiposity and the metabolic risk score attenuated toward the null once they were adjusted for sleep duration (Supplemental Table 5). Associations of WASO and variability with most outcomes remained null regardless of adjustment for sleep duration.

DISCUSSION

This study is 1 of the largest and most comprehensive to date, in which we assess multiple sleep characteristics and adiposity and cardiometabolic outcomes in adolescents. Inadequate sleep as estimated by actigraphy was highly prevalent (31% of adolescents slept <420 minutes, and 42% had sleep efficiencies <85%). Although few children met the National Sleep Foundation–recommended sleep duration, self- or parent-reported sleep duration overestimates sleep compared with actigraphy[48]; additional research is needed to establish normative data by using objective sleep assessments. Adolescents with longer sleep duration and higher sleep efficiency had a more favorable cardiometabolic profile, including components of the metabolic syndrome, namely central adiposity, systolic blood pressure, and HDL cholesterol. Greater sleep efficiency was associated with lower metabolic risk scores independent both of other obesity-related behaviors and of BMI *z* score. These findings are clinically important in that each of the outcomes examined influences not only current cardiometabolic health but also future cardiovascular risk.

Adiposity

Moving beyond the existing literature on sleep duration and BMI,[21,23,49–64] we found that both shorter sleep duration and lower efficiency were associated with central adiposity (waist circumference and DXA trunk fat), which strongly predict risk of diabetes and other metabolic derangements.[65] A limited number of actigraphy studies are used to examine sleep duration and abdominal adiposity in children or adolescents[22,23,27,61,66]; even fewer are used to examine sleep efficiency or DXA trunk fat.[12,19,66,67] Adding new rigor to this evidence, we demonstrate that associations of inadequate sleep with abdominal adiposity are independent of confounders (socioeconomic status) and other obesity-related behaviors.

Metabolic Risk

Sleep duration and efficiency were associated with our aggregate measure of cardiometabolic risk, the metabolic risk score. Although few studies are directly comparable,[66] in adults, both short and extended duration of sleep have longitudinal associations with metabolic risks independent of BMI, including diabetes,[68] hypertension,[69] and hyperlipidemia.[70,71] Meanwhile, with our previous longitudinal work in younger children, we found that the association between parent-reported sleep duration and midchildhood metabolic risk was mediated through midchildhood adiposity (mean age

TABLE 2 Multivariable-Adjusted Associations of Sleep Measures With Adiposity and Cardiometabolic Outcomes

Outcome	Model 1, β (95% CI)	Model 2, β (95% CI)	Model 3, β (95% CI)
Sleep duration (per 55 min)			
BMI *z* score	−0.23 (−0.33, −0.13)	−0.13 (−0.24, −0.03)	—
Waist circumference, cm	−3.06 (−4.12, −2.00)	−2.66 (−3.84, −1.49)	—
Sum of skinfolds, mm	−2.53 (−3.80, −1.26)	−1.85 (−3.22, −0.48)	—
DXA fat mass index, kg/m^2	−0.67 (−1.01, −0.34)	−0.49 (−0.86, −0.11)	—
DXA trunk fat index, kg/m^2	−0.33 (−0.49, −0.17)	−0.24 (−0.42, −0.05)	—
Metabolic risk score	−0.11 (−0.18, −0.03)	−0.08 (−0.17, 0.00)	−0.06 (−0.13, 0.01)
HOMA-IR	−0.34 (−0.58, −0.10)	−0.16 (−0.44, 0.11)	−0.12 (−0.38, 0.14)
Insulin, μU/mL	−2.69 (−4.38, −1.01)	−0.81 (−2.76, 1.14)	−0.93 (−2.78, 0.93)
Glucose, mg/dL	−0.90 (−3.76, 1.97)	0.09 (−3.51, 3.70)	0.37 (−3.22, 3.97)
Systolic blood pressure, mm Hg	−1.73 (−2.53, −0.93)	−1.49 (−2.40, −0.57)	−1.42 (−2.34, −0.51)
Triglycerides, mg/dL	0.73 (−2.88, 4.34)	0.68 (−3.50, 4.85)	1.21 (−2.92, 5.34)
HDL cholesterol, mg/dL	1.66 (0.16, 3.15)	1.63 (−0.12, 3.37)	1.44 (−0.25, 3.14)
Sleep efficiency (per 6%)			
BMI *z* score	−0.05 (−0.15, 0.04)	−0.10 (−0.20, 0.00)	—
Waist circumference, cm	−1.16 (−2.18, −0.14)	−1.65 (−2.76, −0.55)	—
Sum of skinfolds, mm	−0.57 (−1.78, 0.63)	−0.72 (−1.99, 0.56)	—
DXA fat mass index, kg/m^2	−0.17 (−0.50, 0.15)	−0.30 (−0.65, 0.04)	—
DXA trunk fat index, kg/m^2	−0.11 (−0.26, 0.05)	−0.18 (−0.34, −0.01)	—
Metabolic risk score	−0.07 (−0.14, 0.00)	−0.09 (−0.17, −0.01)	−0.08 (−0.14, −0.02)
HOMA-IR	−0.08 (−0.31, 0.14)	−0.11 (−0.37, 0.14)	−0.10 (−0.34, 0.14)
Insulin, μU/mL	−1.80 (−3.35, −0.24)	−0.65 (−2.42, 1.13)	−0.62 (−2.31, 1.07)
Glucose, mg/dL	−2.71 (−5.38, −0.05)	−3.91 (−7.24, −0.58)	−3.80 (−7.12, −0.49)
Systolic blood pressure, mm Hg	−1.17 (−1.93, −0.41)	−1.53 (−2.39, −0.68)	−1.46 (−2.32, −0.61)
Triglycerides, mg/dL	−2.68 (−5.99, 0.62)	−1.16 (−4.98, 2.65)	−0.84 (−4.60, 2.92)
HDL cholesterol, mg/dL	1.47 (0.10, 2.84)	1.65 (0.05, 3.24)	1.46 (−0.08, 3.00)
WASO (per 36 min)			
BMI *z* score	0.00 (−0.10, 0.09)	0.07 (−0.03, 0.16)	—
Waist circumference, cm	0.44 (−0.58, 1.46)	1.03 (−0.07, 2.13)	—
Sum of skinfolds, mm	−0.08 (−1.28, 1.12)	0.18 (−1.08, 1.45)	—
DXA fat mass index, kg/m^2	0.02 (−0.30, 0.33)	0.19 (−0.15, 0.53)	—
DXA trunk fat index, kg/m^2	0.03 (−0.12, 0.18)	0.12 (−0.04, 0.29)	—
Metabolic risk score	0.04 (−0.03, 0.11)	0.06 (−0.02, 0.13)	0.06 (−0.01, 0.12)
HOMA-IR	−0.02 (−0.23, 0.20)	0.04 (−0.20, 0.29)	0.04 (−0.19, 0.28)
Insulin, μU/mL	1.20 (−0.34, 2.73)	0.51 (−1.24, 2.26)	0.52 (−1.15, 2.18)
Glucose, mg/dL	1.51 (−1.08, 4.10)	2.72 (−0.52, 5.97)	2.70 (−0.52, 5.93)
Systolic blood pressure, mm Hg	0.74 (−0.02, 1.50)	1.13 (0.27, 1.98)	1.08 (0.23, 1.93)
Triglycerides, mg/dL	2.87 (−0.39, 6.12)	1.15 (−2.60, 4.90)	0.97 (−2.73, 4.67)
HDL cholesterol, mg/dL	−1.13 (−2.48, 0.22)	−1.30 (−2.87, 0.27)	−1.16 (−2.68, 0.36)
Sleep duration variability (per 35 min)			
BMI *z* score	0.12 (0.03, 0.22)	−0.01 (−0.11, 0.09)	—
Waist circumference, cm	0.90 (−0.13, 1.93)	−0.18 (−1.31, 0.95)	—
Sum of skinfolds, mm	2.06 (0.84, 3.27)	0.79 (−0.51, 2.09)	—
DXA fat mass index, kg/m^2	0.33 (0.01, 0.65)	0.05 (−0.30, 0.41)	—
DXA trunk fat index, kg/m^2	0.15 (0.00, 0.30)	0.03 (−0.15, 0.20)	—
Metabolic risk score	0.03 (−0.04, 0.09)	−0.02 (−0.09, 0.06)	−0.01 (−0.08, 0.05)
HOMA-IR	0.22 (0.00, 0.43)	−0.02 (−0.26, 0.23)	0.00 (−0.23, 0.24)
Insulin, μU/mL	0.89 (−0.67, 2.45)	−0.19 (−1.93, 1.55)	−0.23 (−1.88, 1.43)
Glucose, mg/dL	3.03 (0.45, 5.60)	2.60 (−0.62, 5.82)	2.65 (−0.55, 5.86)
Systolic blood pressure, mm Hg	0.08 (−0.70, 0.85)	0.07 (−0.82, 0.95)	0.08 (−0.80, 0.95)
Triglycerides, mg/dL	−1.18 (−4.50, 2.13)	−2.04 (−5.76, 1.69)	−2.24 (−5.92, 1.44)
HDL cholesterol, mg/dL	0.61 (−0.77, 1.99)	1.36 (−0.20, 2.92)	1.40 (−0.11, 2.91)

Model 1 was adjusted for age and sex. Model 2 comprised model 1 and maternal education and household income, season of measurement, adolescent race and/or ethnicity, puberty (Tanner stage), and obesity-related behaviors (MVPA, television-viewing hours per day, and fast food and sugar-sweetened beverage servings per day). Model 3 comprised model 2 and BMI *z* score (for cardiometabolic biomarkers only). —, not applicable.

was 7 years).[37] Here, we examine the same cohort as they enter adolescence (mean age was 13 years) and estimate sleep duration and efficiency using actigraphy. As before, the association of sleep duration with the metabolic risk score is dependent on BMI *z* score; however, sleep efficiency was associated with metabolic risk independent of BMI *z* score, suggesting that adolescent sleep quality, as measured by increased waking during the sleep period, contributes to cardiometabolic health through pathways other than BMI.

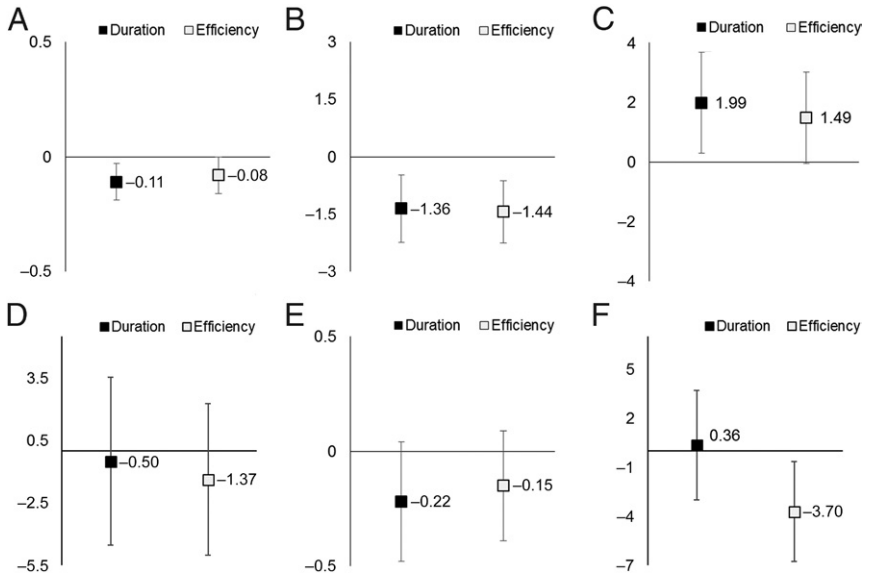

FIGURE 2

Multivariable-adjusted associations of sleep duration and efficiency (per interquartile increase) with cardiometabolic biomarker outcomes. Results for cardiometabolic outcomes are shown per IQR of the following sleep exposures: duration (55 minutes) and efficiency (6%). Models adjust for maternal education and household income, season of measurement, and adolescent age, sex, race and/or ethnicity, and puberty (Tanner stage). A, Metabolic risk score (points). B, Systolic blood pressure (in millimeters of mercury). C, HDL cholesterol (in milligrams per deciliter). D, Triglycerides (in milligrams per deciliter). E, HOMA-IR. F, Glucose (in milligrams per deciliter).

Blood Pressure and Blood Lipids

We observed associations of sleep duration and efficiency with higher systolic blood pressure independent of BMI *z* score and obesity-related behaviors. Although the literature on sleep and blood pressure is sparse among children and adolescents,[20,24,25,72] authors of the few existing studies in which sleep is objectively measured confirm our findings: authors of an early study of this topic found that low efficiency and short duration were both associated with higher odds of prehypertension among adolescents.[17] With respect to blood lipids, we found that longer sleep was associated with higher HDL cholesterol in all subjects and with lower triglycerides in girls only. Although authors of some studies in which objectively measured sleep was researched found inverse associations of sleep duration with triglycerides,[27,73] most authors have not observed associations with HDL cholesterol.[66,73] This makes our finding that greater sleep efficiency is associated with higher HDL cholesterol independent of other obesity-related behaviors of particular interest.

Glucose Homeostasis

The associations of sleep duration with glucose homeostasis are understudied and inconsistent among children and adolescents, perhaps because of the challenge of obtaining fasting blood samples.[22,66] Although we found no statistically significant associations with HOMA-IR or insulin, we found that higher sleep efficiency was associated with lower glucose. Authors of other actigraphy studies reported an inverse association between sleep duration and HOMA-IR,[22,66] or a U-shaped relationship,[21] depending on the participant age and study design. For example, authors of a Danish study found no cross-sectional association of HOMA-IR, but they found that longitudinally positive changes in sleep duration were associated with beneficial changes in HOMA-IR.[66]

Sex Differences

We found associations of sleep efficiency and WASO with triglycerides and variability with adiposity only among girls; others have also found effect modification by sex when examining sleep characteristics. For example, authors of the Cleveland Study found that the association between short sleep and dietary fat intake was stronger in girls,[74] whereas its association with BMI and glucose homeostasis was stronger in boys.[22] Authors of adult experimental studies also report that female subjects have a greater inflammatory and immune response to sleep restriction than male subjects.[75] Sex may modify the physiologic response to sleep disturbance. The complex interrelationship of sex hormones, sleep, and obesity-related behaviors in adolescence warrants further investigation.

Sleep Quantity Versus Sleep Quality

The associations of sleep duration and efficiency with systolic blood pressure were robust to mutual adjustment, were used to underscore that both quantity and quality or continuity of sleep are both important to cardiometabolic health in adolescence. Typically, sleep duration and efficiency are examined in separate models; authors of few studies reported independent associations.[20] For example, in Danish children, sleep efficiency was associated with waist circumference after adjustment for sleep duration,[66] and others have found that sleep efficiency[23] and variability,[19] but not duration, are associated with greater adiposity. This runs counter to our finding that although duration was associated with BMI *z* score, and waist circumference was independent of efficiency, associations of efficiency with adiposity outcomes attenuated after adjusting for duration.

Proposed Mechanisms

Several proposed mechanisms can be used to explain the association between sleep duration and quality and cardiometabolic health,[76–78] including physiologic and behavioral changes that impact energy intake and expenditure. In adults[79–88] and, to a limited extent, in children[89] and adolescents,[90,91] authors of experimental research suggest that inadequate sleep duration leads to increased energy intake, altered food choices, changes in the brain's response to reward stimuli,[77] lowered leptin, and increased ghrelin.[81] Inadequate quantity and quality of sleep have also been associated with decreased physical activity, increased screen time,[92,93] decreased fat oxidation,[77] and abnormalities in the autonomic nervous system and hypothalamus-pituitary-adrenocortical axis.[77,78] These, in turn, influence the metabolic outcomes examined in this study including abdominal adiposity, insulin resistance, dyslipidemia, and elevated blood pressure. Although this web of bidirectional relationships cannot be disentangled in a cross-sectional study, it is striking that many of the associations were independent both of BMI *z* score and of obesity-related behaviors including MVPA, television-viewing, and fast food and sugar-sweetened beverage intake.

Clinical Implications

Although causality cannot be determined from cross-sectional data, pediatricians should be aware that poor sleep quality (eg, frequent awakenings) and not just insufficient duration of sleep is associated with increased cardiometabolic risk. Optimizing children's health should include strategies used to address child and adolescent sleep, including duration and efficiency, and to screen for sleep problems and disorders. Although greater clarity is needed on the independent effects of sleep quantity and quality, with our findings, we suggest that both sleep duration and efficiency are associated with cardiometabolic health in early adolescence. Intervention trials have been used to attempt to extend sleep duration, but few have been used to target sleep efficiency or other aspects of sleep quality. In adults, exercise increases sleep efficiency,[94,95] and in children, television-viewing and other forms of screen time reduce sleep efficiency. Preventive interventions to improve sleep health should be used to target behavioral and environmental factors that influence sleep continuity as well as duration, such as screen time,[96] stress, noise, caffeine, and exercise.[95] Such multimodal interventions are likely to improve multiple aspects of sleep.[97]

Strengths and Limitations

Among its strengths, this study was used to objectively measure sleep quantity as well as sleep quality in relation to a composite metabolic risk score and its components. The use of data from a well-established cohort of adolescents managed since birth allowed us to address the limitations of previous studies through control for sociodemographic confounders and obesity-related behaviors. However, our study was cross-sectional, a key limitation that complicates its interpretation; longitudinal studies with repeated, objective measures are needed to establish the temporal order of inadequate sleep and metabolic risk. In addition, although actigraphy is a practical method used to measure sleep over multiple days with minimal participant burden,[98] actigraphy differs from the gold standard (polysomnography),[48] and there are important exposures (eg, sleep stage distribution) not captured by actigraphy.[78]

CONCLUSIONS

Sleep quantity and quality are associated with a more favorable cardiometabolic profile in early adolescence. Although associations vary by sleep parameter or metabolic marker examined, they are strongest and most consistent for sleep duration and efficiency in relationship to central adiposity and blood pressure. BMI and obesity-related behaviors cannot be used to account fully for the associations, which suggests there may be additional physiologic pathways such as abnormalities in hypothalamic-pituitary-adrenal axis and the autonomic nervous system that account for sleep's influence on cardiometabolic health in early adolescence. Sleep quantity and quality are pillars of health alongside diet and physical activity, and authors of future studies should examine intervention strategies to improve sleep quality as well as quantity in adolescents.

ABBREVIATIONS

CI: confidence interval
DXA: dual-energy radiograph absorptiometry
HDL: high-density lipoprotein
HOMA-IR: homeostatic model assessment of insulin resistance
IQR: interquartile range
MVPA: moderate-to-vigorous physical activity
WASO: wake after sleep onset

all analyses; and all authors approved, revised, and critically reviewed the manuscript for important intellectual content and the final manuscript as submitted and agree to be accountable for all aspects of the work.

DOI: https://doi.org/10.1542/peds.2017-4085

Accepted for publication Apr 10, 2018

Address correspondence to Elizabeth M. Cespedes Feliciano, ScD, MSc, Division of Research, Kaiser Permanente Northern California, 2000 Broadway, 5th Floor, Oakland, CA 94610. E-mail: elizabeth.m.cespedes@kp.org

PEDIATRICS (ISSN Numbers: Print, 0031-4005; Online, 1098-4275).

FINANCIAL DISCLOSURE: The authors have indicated they have no financial relationships relevant to this article to disclose.

FUNDING: Supported by the National Institute of Child Health and Human Development, the National Institute of Diabetes and Digestive and Kidney Diseases, and National Heart, Lung, and Blood Institute of the National Institutes of Health under award numbers U54CA116847, R01HD034568, UG3OD023286, P30 DK092924, K24 DK10589, and R35 HL135818. Dr Quante was supported by a scholarship from the Tuebinger Program for the Advancement of Women in Science. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. Funded by the National Institutes of Health (NIH).

POTENTIAL CONFLICT OF INTEREST: The authors have indicated they have no potential conflicts of interest to disclose.

REFERENCES

1. Aatola H, Koivistoinen T, Tuominen H, et al. Influence of child and adult elevated blood pressure on adult arterial stiffness: the cardiovascular risk in Young Finns study. *Hypertension*. 2017;70(3):531–536
2. Ajala O, Mold F, Boughton C, Cooke D, Whyte M. Childhood predictors of cardiovascular disease in adulthood. A systematic review and meta-analysis. *Obes Rev*. 2017;18(9):1061–1070
3. Nuotio J, Pitkänen N, Magnussen CG, et al. Prediction of adult dyslipidemia using genetic and childhood clinical risk factors: the cardiovascular risk in Young Finns study. *Circ Cardiovasc Genet*. 2017;10(3):e001604
4. Fatima Y, Doi SA, Mamun AA. Longitudinal impact of sleep on overweight and obesity in children and adolescents: a systematic review and bias-adjusted meta-analysis. *Obes Rev*. 2015;16(2):137–149
5. Cappuccio FP, Taggart FM, Kandala N-B, et al. Meta-analysis of short sleep duration and obesity in children and adults. *Sleep*. 2008;31(5):619–626
6. Taveras EM, Gillman MW, Peña MM, Redline S, Rifas-Shiman SL. Chronic sleep curtailment and adiposity. *Pediatrics*. 2014;133(6): 1013–1022
7. Cespedes EM, Hu FB, Redline S, et al. Chronic insufficient sleep and diet quality: contributors to childhood obesity. *Obesity (Silver Spring)*. 2016;24(1):184–190
8. Chaput JP, Gray CE, Poitras VJ, et al. Systematic review of the relationships between sleep duration and health indicators in school-aged children and youth. *Appl Physiol Nutr Metab*. 2016;41(6, suppl 3):S266–S282
9. Matthews KA, Pantesco EJ. Sleep characteristics and cardiovascular risk in children and adolescents: an enumerative review. *Sleep Med*. 2016;18:36–49
10. Quist JS, Sjödin A, Chaput J-P, Hjorth MF. Sleep and cardiometabolic risk in children and adolescents. *Sleep Med Rev*. 2016;29:76–100
11. Fernandez-Mendoza J, Baker JH, Vgontzas AN, Gaines J, Liao D, Bixler EO. Insomnia symptoms with objective short sleep duration are associated with systemic inflammation in adolescents. *Brain Behav Immun*. 2017;61:110–116
12. Klingenberg L, Christensen LB, Hjorth MF, et al. No relation between sleep duration and adiposity indicators in 9-36 months old children: the SKOT cohort. *Pediatr Obes*. 2013;8(1):e14–e18
13. Zhu Y, Li AM, Au CT, et al. Association between sleep architecture and glucose tolerance in children and adolescents. *J Diabetes*. 2015;7(1):10–15
14. Koren D, Levitt Katz LE, Brar PC, Gallagher PR, Berkowitz RI, Brooks LJ. Sleep architecture and glucose and insulin homeostasis in obese adolescents. *Diabetes Care*. 2011;34(11):2442–2447
15. Flint J, Kothare SV, Zihlif M, et al. Association between inadequate sleep and insulin resistance in obese children. *J Pediatr*. 2007;150(4):364–369
16. Armitage R, Lee J, Bertram H, Hoffmann R. A preliminary study of slow-wave EEG activity and insulin sensitivity in adolescents. *Sleep Med*. 2013;14(3):257–260
17. Archbold KH, Vasquez MM, Goodwin JL, Quan SF. Effects of sleep patterns and obesity on increases in blood pressure in a 5-year period: report from the Tucson Children's Assessment of Sleep Apnea Study. *J Pediatr*. 2012;161(1):26–30
18. Hall MH, Lee L, Matthews KA. Sleep duration during the school week is associated with C-reactive protein risk groups in healthy adolescents. *Sleep Med*. 2015;16(1):73–78
19. He F, Bixler EO, Liao J, et al. Habitual sleep variability, mediated by nutrition intake, is associated with abdominal obesity in adolescents. *Sleep Med*. 2015;16(12):1489–1494
20. Javaheri S, Storfer-Isser A, Rosen CL, Redline S. Sleep quality and elevated blood pressure in adolescents. *Circulation*. 2008;118(10): 1034–1040
21. Javaheri S, Storfer-Isser A, Rosen CL, Redline S. Association of short and long sleep durations with insulin sensitivity in adolescents. *J Pediatr*. 2011;158(4):617–623
22. Matthews KA, Dahl RE, Owens JF, Lee L, Hall M. Sleep duration and insulin resistance in healthy black and white adolescents. *Sleep*. 2012;35(10):1353–1358
23. Mcneil J, Tremblay MS, Leduc G, et al. Objectively-measured sleep and its association with adiposity and physical activity in a sample of Canadian children. *J Sleep Res*. 2015;24(2):131–139

24. Meininger JC, Gallagher MR, Eissa MA, Nguyen TQ, Chan W. Sleep duration and its association with ambulatory blood pressure in a school-based, diverse sample of adolescents. *Am J Hypertens*. 2014;27(7):948–955

25. Mezick EJ, Hall M, Matthews KA. Sleep duration and ambulatory blood pressure in black and white adolescents. *Hypertension*. 2012;59(3):747–752

26. Park H, Tsai KM, Dahl RE, et al. Sleep and inflammation during adolescence. *Psychosom Med*. 2016;78(6): 677–685

27. Sung V, Beebe DW, Vandyke R, et al. Does sleep duration predict metabolic risk in obese adolescents attending tertiary services? A cross-sectional study. *Sleep*. 2011;34(7): 891–898

28. Colrain IM, Baker FC. Changes in sleep as a function of adolescent development. *Neuropsychol Rev*. 2011;21(1):5–21

29. Iglowstein I, Jenni OG, Molinari L, Largo RH. Sleep duration from infancy to adolescence: reference values and generational trends. *Pediatrics*. 2003;111(2):302–307

30. Zimmet P, Alberti KGM, Kaufman F, et al; IDF Consensus Group. The metabolic syndrome in children and adolescents - an IDF consensus report. *Pediatr Diabetes*. 2007;8(5):299–306

31. Cole RJ, Kripke DF, Gruen W, Mullaney DJ, Gillin JC. Automatic sleep/wake identification from wrist activity. *Sleep*. 1992;15(5):461–469

32. Ogden CL, Kuczmarski RJ, Flegal KM, et al. Centers for Disease Control and Prevention 2000 growth charts for the United States: improvements to the 1977 National Center for Health Statistics version. *Pediatrics*. 2002;109(1):45–60

33. Barlow SE; Expert Committee. Expert committee recommendations regarding the prevention, assessment, and treatment of child and adolescent overweight and obesity: summary report. *Pediatrics*. 2007;120(suppl 4):S164–S192

34. Louer AL, Simon DN, Switkowski KM, Rifas-Shiman SL, Gillman MW, Oken E. Assessment of child anthropometry in a large epidemiologic study. *J Vis Exp*. 2017;(120)

35. Perng W, Gillman MW, Mantzoros CS, Oken E. A prospective study of maternal prenatal weight and offspring cardiometabolic health in midchildhood. *Ann Epidemiol*. 2014;24(11):793–800.e1

36. Chatzi L, Rifas-Shiman SL, Georgiou V, et al. Adherence to the Mediterranean diet during pregnancy and offspring adiposity and cardiometabolic traits in childhood. *Pediatr Obes*. 2017;12(suppl 1):47–56

37. Cespedes EM, Rifas-Shiman SL, Redline S, Gillman MW, Peña MM, Taveras EM. Longitudinal associations of sleep curtailment with metabolic risk in mid-childhood. *Obesity (Silver Spring)*. 2014;22(12):2586–2592

38. Viitasalo A, Lakka TA, Laaksonen DE, et al. Validation of metabolic syndrome score by confirmatory factor analysis in children and adults and prediction of cardiometabolic outcomes in adults. *Diabetologia*. 2014;57(5): 940–949

39. Eisenmann JC, Laurson KR, DuBose KD, Smith BK, Donnelly JE. Construct validity of a continuous metabolic syndrome score in children. *Diabetol Metab Syndr*. 2010;2:8

40. De Ferranti SD, Osganian SK. Epidemiology of paediatric metabolic syndrome and type 2 diabetes mellitus. *Diab Vasc Dis Res*. 2007;4(4): 285–296

41. Chandler JL, Brazendale K, Beets MW, Mealing BA. Classification of physical activity intensities using a wrist-worn accelerometer in 8-12-year-old children. *Pediatr Obes*. 2016;11(2):120–127

42. Morris NM, Udry JR. Validation of a self-administered instrument to assess stage of adolescent development. *J Youth Adolesc*. 1980;9(3):271–280

43. Zhang G, Wu L, Zhou L, Lu W, Mao C. Television watching and risk of childhood obesity: a meta-analysis. *Eur J Public Health*. 2016;26(1):13–18

44. Cespedes EM, Gillman MW, Kleinman K, Rifas-Shiman SL, Redline S, Taveras EM. Television viewing, bedroom television, and sleep duration from infancy to mid-childhood. *Pediatrics*. 2014;133(5). Available at: www.pediatrics.org/cgi/content/full/133/5/e1163

45. Marinelli M, Sunyer J, Alvarez-Pedrerol M, et al. Hours of television viewing and sleep duration in children: a multicenter birth cohort study. *JAMA Pediatr*. 2014;168(5):458–464

46. Marinelli M. Impact of television on the quality of sleep in preschool children. *Sleep Med*. 2016;20:138–139

47. Hirshkowitz M, Whiton K, Albert SM, et al. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. *Sleep Health*. 2015;1(1):40–43

48. Tryon WW. Issues of validity in actigraphic sleep assessment. *Sleep*. 2004;27(1):158–165

49. Yu Y, Lu BS, Wang B, et al. Short sleep duration and adiposity in Chinese adolescents. *Sleep*. 2007;30(12):1688–1697

50. Sokolovic N, Kuriyan R, Kurpad AV, Thomas T. Sleep and birthweight predict visceral adiposity in overweight/obese children. *Pediatr Obes*. 2013;8(3):e41–e44

51. Shaikh WA, Patel M, Singh S. Association of sleep duration with arterial blood pressure profile of Gujarati Indian adolescents. *Indian J Community Med*. 2010;35(1): 125–129

52. Narang I, Manlhiot C, Davies-Shaw J, et al. Sleep disturbance and cardiovascular risk in adolescents. *CMAJ*. 2012;184(17):E913–E920

53. Lee JA, Park HS. Relation between sleep duration, overweight, and metabolic syndrome in Korean adolescents. *Nutr Metab Cardiovasc Dis*. 2014;24(1):65–71

54. Kuriyan R, Thomas T, Sumithra S, et al. Potential factors related to waist circumference in urban South Indian children. *Indian Pediatr*. 2012;49(2):124–128

55. Jiang YR, Spruyt K, Chen WJ, et al. Associations between parent-reported sleep duration and adiposity in Chinese early adolescents. *J Public Health (Oxf)*. 2015;37(2):277–285

56. Jarrin DC, McGrath JJ, Drake CL. Beyond sleep duration: distinct sleep dimensions are associated with

obesity in children and adolescents. *Int J Obes (Lond)*. 2013;37(4):552–558

57. Hitze B, Bosy-Westphal A, Bielfeldt F, et al. Determinants and impact of sleep duration in children and adolescents: data of the Kiel Obesity Prevention Study. *Eur J Clin Nutr*. 2009;63(6):739–746
58. Guo X, Zheng L, Li Y, et al. Association between sleep duration and hypertension among Chinese children and adolescents. *Clin Cardiol*. 2011;34(12):774–781
59. Garaulet M, Ortega FB, Ruiz JR, et al. Short sleep duration is associated with increased obesity markers in European adolescents: effect of physical activity and dietary habits. The HELENA study. *Int J Obes (Lond)*. 2011;35(10):1308–1317
60. Chaput JP, Brunet M, Tremblay A. Relationship between short sleeping hours and childhood overweight/obesity: results from the 'Québec en Forme' Project. *Int J Obes (Lond)*. 2006;30(7):1080–1085
61. Biggs SN, Dollman J. Association between sleep, BMI and waist girth in children and adolescents: a retrospective analysis. *Acta Paediatr*. 2007;96(12):1839–1840
62. Azadbakht L, Kelishadi R, Khodarahmi M, et al. The association of sleep duration and cardiometabolic risk factors in a national sample of children and adolescents: the CASPIAN III study. *Nutrition*. 2013;29(9):1133–1141
63. Altenburg TM, Chinapaw MJM, van der Knaap ETW, Brug J, Manios Y, Singh AS. Longer sleep–slimmer kids: the ENERGY-project. *PLoS One*. 2013;8(3):e59522
64. Al-Hazzaa HM. Joint associations of body mass index and waist-to-height ratio with sleep duration among Saudi adolescents. *Ann Hum Biol*. 2014;41(2):111–117
65. Després JP, Lemieux I, Bergeron J, et al. Abdominal obesity and the metabolic syndrome: contribution to global cardiometabolic risk. *Arterioscler Thromb Vasc Biol*. 2008;28(6):1039–1049
66. Hjorth MF, Chaput JP, Damsgaard CT, et al. Low physical activity level and short sleep duration are associated with an increased cardio-metabolic risk profile: a longitudinal study in 8-11 year old Danish children. *PLoS One*. 2014;9(8):e104677
67. Hjorth MF, Chaput JP, Ritz C, et al. Fatness predicts decreased physical activity and increased sedentary time, but not vice versa: support from a longitudinal study in 8- to 11-year-old children. *Int J Obes (Lond)*. 2014;38(7):959–965
68. Shan Z, Ma H, Xie M, et al. Sleep duration and risk of type 2 diabetes: a meta-analysis of prospective studies. *Diabetes Care*. 2015;38(3):529–537
69. Jackowska M, Steptoe A. Sleep and future cardiovascular risk: prospective analysis from the English Longitudinal Study of Ageing. *Sleep Med*. 2015;16(6):768–774
70. Petrov ME, Kim Y, Lauderdale D, et al. Longitudinal associations between objective sleep and lipids: the CARDIA study. *Sleep*. 2013;36(11):1587–1595
71. Kinuhata S, Hayashi T, Sato KK, et al. Sleep duration and the risk of future lipid profile abnormalities in middle-aged men: the Kansai Healthcare Study. *Sleep Med*. 2014;15(11):1379–1385
72. Martikainen S, Pesonen AK, Feldt K, et al. Poor sleep and cardiovascular function in children. *Hypertension*. 2011;58(1):16–21
73. Spruyt K, Molfese DL, Gozal D. Sleep duration, sleep regularity, body weight, and metabolic homeostasis in school-aged children. *Pediatrics*. 2011;127(2). Available at: www.pediatrics.org/cgi/content/full/127/2/e345
74. Weiss A, Xu F, Storfer-Isser A, Thomas A, Ievers-Landis CE, Redline S. The association of sleep duration with adolescents' fat and carbohydrate consumption. *Sleep*. 2010;33(9):1201–1209
75. Faraut B, Boudjeltia KZ, Vanhamme L, Kerkhofs M. Immune, inflammatory and cardiovascular consequences of sleep restriction and recovery. *Sleep Med Rev*. 2012;16(2):137–149
76. Gozal D, Khalyfa A, Qiao Z, Akbarpour M, Maccari R, Ottanà R. Protein-tyrosine phosphatase-1B mediates sleep fragmentation-induced insulin resistance and visceral adipose tissue inflammation in mice. *Sleep*. 2017;40(9)
77. Schmid SM, Hallschmid M, Schultes B. The metabolic burden of sleep loss. *Lancet Diabetes Endocrinol*. 2015;3(1):52–62
78. Tasali E, Leproult R, Ehrmann DA, Van Cauter E. Slow-wave sleep and the risk of type 2 diabetes in humans. *Proc Natl Acad Sci USA*. 2008;105(3):1044–1049
79. Markwald RR, Melanson EL, Smith MR, et al. Impact of insufficient sleep on total daily energy expenditure, food intake, and weight gain. *Proc Natl Acad Sci USA*. 2013;110(14):5695–5700
80. St-Onge MP, Roberts AL, Chen J, et al. Short sleep duration increases energy intakes but does not change energy expenditure in normal-weight individuals. *Am J Clin Nutr*. 2011;94(2):410–416
81. Spiegel K, Tasali E, Penev P, Van Cauter E. Brief communication: sleep curtailment in healthy young men is associated with decreased leptin levels, elevated ghrelin levels, and increased hunger and appetite. *Ann Intern Med*. 2004;141(11):846–850
82. Spaeth AM, Dinges DF, Goel N. Sex and race differences in caloric intake during sleep restriction in healthy adults. *Am J Clin Nutr*. 2014;100(2):559–566
83. Spaeth AM, Dinges DF, Goel N. Effects of experimental sleep restriction on weight gain, caloric intake, and meal timing in healthy adults. *Sleep*. 2013;36(7):981–990
84. Capers PL, Fobian AD, Kaiser KA, Borah R, Allison DB. A systematic review and meta-analysis of randomized controlled trials of the impact of sleep duration on adiposity and components of energy balance. *Obes Rev*. 2015;16(9):771–782
85. Calvin AD, Carter RE, Adachi T, et al. Effects of experimental sleep restriction on caloric intake and activity energy expenditure. *Chest*. 2013;144(1):79–86
86. Broussard JL, Kilkus JM, Delebecque F, et al. Elevated ghrelin predicts food intake during experimental sleep restriction. *Obesity (Silver Spring)*. 2016;24(1):132–138

87. Brondel L, Romer MA, Nougues PM, Touyarou P, Davenne D. Acute partial sleep deprivation increases food intake in healthy men. *Am J Clin Nutr*. 2010;91(6):1550–1559

88. Bosy-Westphal A, Hinrichs S, Jauch-Chara K, et al. Influence of partial sleep deprivation on energy balance and insulin sensitivity in healthy women. *Obes Facts*. 2008;1(5):266–273

89. Mullins EN, Miller AL, Cherian SS, et al. Acute sleep restriction increases dietary intake in preschool-age children. *J Sleep Res*. 2017;26(1): 48–54

90. Klingenberg L, Chaput JP, Holmbäck U, Jennum P, Astrup A, Sjödin A. Sleep restriction is not associated with a positive energy balance in adolescent boys. *Am J Clin Nutr*. 2012;96(2):240–248

91. Beebe DW, Simon S, Summer S, Hemmer S, Strotman D, Dolan LM. Dietary intake following experimentally restricted sleep in adolescents. *Sleep*. 2013;36(6):827–834

92. Hart CN, Hawley N, Davey A, et al. Effect of experimental change in children's sleep duration on television viewing and physical activity. *Pediatr Obes*. 2017;12(6):462–467

93. Schmid SM, Hallschmid M, Jauch-Chara K, et al. Short-term sleep loss decreases physical activity under free-living conditions but does not increase food intake under time-deprived laboratory conditions in healthy men. *Am J Clin Nutr*. 2009;90(6): 1476–1482

94. Dolezal BA, Neufeld EV, Boland DM, Martin JL, Cooper CB. Interrelationship between sleep and exercise: a systematic review. *Adv Prev Med*. 2017;2017:1364387

95. Irish LA, Kline CE, Gunn HE, Buysse DJ, Hall MH. The role of sleep hygiene in promoting public health: a review of empirical evidence. *Sleep Med Rev*. 2015;22:23–36

96. Hale L, Guan S. Screen time and sleep among school-aged children and adolescents: a systematic literature review. *Sleep Med Rev*. 2015;21:50–58

97. Cain N, Gradisar M. Electronic media use and sleep in school-aged children and adolescents: a review. *Sleep Med*. 2010;11(8):735–742

98. Quante M, Kaplan ER, Rueschman M, Cailler M, Buxton OM, Redline S. Practical considerations in using accelerometers to assess physical activity, sedentary behavior, and sleep. *Sleep Health*. 2015;1(4):275–284