Sleep duration and quality as mediators of socioeconomic disparities in inflammatory burden

Renson, A.

# Introduction

Sleep deficiency, which includes insufficient and poor quality sleep, represents a growing public health problem in the United States. Nearly 30% of adults in the U.S. report sleeping 6 or fewer hours per night,1 20% report excessive daytime sleepiness, and 20-30% experience insomnia symptoms.2 A growing body of literature links poor sleep duration and quality to a number of health outcomes, including all-cause mortality,3,4 as well as incidence of type 2 diabetes,5,6 hypertension,7 coronary heart disease,8 and stroke9. Specifically, meta-analyses support a “U-shaped” association in which both short and long sleep (generally <6 and >8 hours, respectively) are related to elevated all-cause mortality risk.3,4

An important factor linking sleep and many chronic diseases may be low-grade, systemic inflammation, commonly measured by plasma concentrations of the immune markers interleukin-6 (IL-6), fibrinogen, tumor necrosis factor-a, and c-reactive protein (CRP). The most extensively studied biomarker of inflammation is c-reactive protein (CRP), an acute phase reactant (chemicals accompanying inflammatory pathway activation), for which high sensitivity assays are widely available.10 Based on Mendelian randomization studies, CRP itself is unlikely to be a causal risk factor of metabolic syndrome11 or ischemic vascular disease,12 although limited human experimental evidence suggests it has an etiologic role in atherosclerosis.13 CRP has a complex role in inflammation and its primary function may be anti-inflammatory;14 nonetheless, it is a useful biomarker corresponding to general, potentially subclinical risk.

CRP is best characterized in relation to cardiovascular disease (CVD), as it is a strong predictor of cardiovascular events.15-17 Extensive experimental and observational evidence ties inflammatory processes marked by CRP to atherogenesis, the primary pathogenic process underlying coronary heart disease (CHD).18 CRP is also a potent risk factor for all-cause mortality,19 and is associated with incidence of metabolic syndrome,16 colorectal cancer,20 and end stage renal disease,21 indicating inflammation may be an underlying pathogenic process shared by many chronic diseases. Short (<6 hours) and poor quality sleep have been shown to affect inflammation in experimental studies22,23 and to be associated with CRP and IL-6 in observational studies.24-26 Sleep restriction induces changes in glucose tolerance, thyrotropin concentration, evening cortisol concentrations, and sympathetic nervous activity, alterations which have implications in inflammation.27

A central challenge in public health is tackling socioeconomic disparities in health outcomes. Graded, inverse associations between socioeconomic status (SES) and a broad array of health outcomes, including CVD, diabetes, hypertension, a number of cancers, and all-cause mortality, have been extensively documented by a long history of research.28,29 More recently, a number of studies have observed socioeconomic disparities in inflammatory burden, with CRP, IL-6, and fibrinogen being consistently elevated in lower SES categories.30-33

Commonly hypothesized pathways for the impact of SES on inflammation are health status, behavioral (smoking, physical activity) and psychosocial (stress etc.) factors,31,34 and sleep may represent an underexplored link in this causal chain. Sleep restriction35 and poor quality sleep36,37 have been found to be more prevalent among individuals of low SES. Low income and low education are associated with adverse social and environmental conditions that impede adequate sleep38 and a growing number of lower-paid jobs involve precarious shift work and non-standard hours.39 Sleep is a modifiable risk factor for which efficacious non-pharmacological interventions exist.40 However, to our knowledge, no study has examined whether sleep mediates the relationship between SES and inflammation. The purpose of this study was to assess the role of short duration (<6 hours per night) and poor quality sleep as potential mediators between SES measures such as income and education, and inflammatory burden marked by plasma CRP.

# Methods

## Datasets

We used data from the continuous National Health and Nutritional Examination Survey (NHANES), an ongoing cross-sectional survey of the civilian non-institutionalized population in the United States. Data were collected by the National Center for Health Statistics and the Centers for Disease Control and Prevention (CDC) and involve a questionnaire, physical exam, and laboratory measures. Detailed descriptions of the survey methodology and operations are published elsewhere.41 In brief, NHANES uses a stratified, multistage, probability sample, with oversampling for Hispanics, non-Hispanic Blacks, low-income whites, and persons age 70 and over (1999-2006) or 80 and over (2007-2010). Individuals agreeing to participate completed an in-home, computer-assisted interview conducted by trained personnel, with physical examinations and laboratory sample collection conducted at the Mobile Examination Centers (MECs). Approximately 12,000 people were approached each two-year cycle, of whom an average of 10,000 ultimately completed the household interview and data collection at the MEC, for a response rate of approximately 83.3%.

We used questionnaire, physical exam, and laboratory data from 3 waves spanning 2005-2010. We selected all respondents aged 20 years and older, who had complete data for CRP and answered questions on sleep duration and quality. We excluded individuals who had CRP concentrations greater than 10 mg/L, which indicate acute infection or insult.17 We also excluded pregnant women, who demonstrate elevated and/or unstable CRP.17

## Measures

### Exposure Variables

In addition to raw family income, NHANES also reports the poverty income ratio (PIR), a ratio of family income to federal poverty level (FPL), which was chosen for this analysis because it takes into account family size and more accurately represents available financial resources. We categorized PIR as poor (below FPL), nearly poor (100-199% FPL), and middle and high income (≥200% FPL), according to the CDC’s Healthy People 2020 guidelines (<https://www.healthypeople.gov/2020/disparities-user-guide>).

In addition to family income, the most commonly used measure of SES, we also used highest educational level achieved, a measure that is more stable throughout the life course and a stronger predictor of inflammation than income.42 NHANES measures education with the question, “What is the highest grade or level of school [you have/spouse has] completed or the highest degree [you have/s/he has] received?”, with the options “Less than 9th Grade”, “9-11th Grade (Includes 12th grade with no diploma)”, “High School Grad/GED or Equivalent”, “Some College or AA degree”, “College Graduate or above”.

### Mediator Variables

Sleep quality was operationalized according to the method used by Bansil et al.:7 participants were characterized as having poor sleep quality if they reported 5 or more episodes in the previous month of one or more of the following events: (i) having trouble falling asleep; (ii) waking up during the night and having trouble getting back to sleep; (iii) waking up too early in the morning and being unable to get back to sleep; (iv) feeling unrested during the day, no matter how many hours of sleep he/she had; or (v) feeling excessively or overly sleepy during the day. Short sleep was categorized based on an answer to the question, “How much sleep [do you/does SP] usually get at night on weekdays or workdays?”, with participants coded as having short sleep if they reported sleeping less than 6 hours, similarly to other population-based studies.25

### Outcome Variables

C-reactive protein is measured from blood collected during the physical exam and processed, stored, and shipped to a Johns Hopkins University laboratory. Plasma CRP concentrations are quantified by high sensitivity assay using latex-enhanced nephelometry, with a lower limit of detection of 0.1 mg/L.41 We transformed c-reactive protein using the natural logarithm, as CRP values have been observed to be right skewed and heteroskedastic with a mean-variance relationship (Pollitt 2008, Phillips 2009, Matthews 2016).

### Confounding Variables

We considered a number of potential confounders of the relationship between sleep and CRP, based on being a potential common cause (or proxy to a common cause) of both sleep and CRP. Analyses were adjusted for age (in 5-year categories), sex (male or female), race/ethnicity (non-Hispanic White, non-Hispanic Black, Mexican American, Other Hispanic, and Other Race including Multi-Racial), physical activity (number of times per week exercising enough to sweat or breathe hard), current tobacco use indicated by serum cotinine > 3 ng/mL43, obesity (body mass index (BMI) >= 30 kg/m2, measured in the physical exam), psychosocial stress (number of days in the past 30 when mental health was not good), use of birth control pills or hormone replacement therapy, and use of sleep medications often or almost always (5 or more times per month).

We separately considered potential confounders of the relationship between SES and CRP, which included only age. Although previous studies of this relationship have adjusted for serious chronic conditions,31,32 we chose to consider this variable a potential collider and not adjust for it. Final models were adjusted for all variables considered confounders of the SES → CRP and/or sleep → CRP relationships.

## Data Analysis

We summarized all variables in the overall sample as well as stratified by sleep duration and sleep quality. All variables are presented as unweighted n, as well as weighted percent for categorical variables, and weighted median [range or interquartile range (IQR)] for continuous variables. C-reactive protein is summarized as a geometric mean and log transformed in all analyses. We tested crude associations between each of the exposure, mediator, and confounding variables and geometric mean CRP using one-way ANOVA with log-transformed CRP as the response variable.

### Assessment of Mediation

We sought to assess whether sleep duration and quality were intermediate variables in the causal pathway between SES and inflammation. Therefore, data analysis focused on assessment of total indirect effect (TIE),44 or the proportion of inflammation that would be prevented if SES did not cause poor sleep.44 We determined that potential mediation existed if (a) the exposure was associated with the outcome, (b) the exposure was associated with the mediator, and (c) the mediator was associated with the outcome, each after adjusting for all potential confounders, based on a significant likelihood ratio test using logistic regression for binary variables, and type III sum of squares f-test from multi-way ANOVA for continuous variables.

If these conditions were met, we then tested for mediation using the product-of-coefficients method that allows for interaction between the exposure and the mediator, detailed by VanderWheel (2016).45 This was accomplished by fitting two least squares linear regression models for each hypothesized exposure-mediator combination: (1) we regressed the mediator on the exposure and all potential confounders, and (2) we regressed the outcome on the exposure, mediator, exposure-mediator product, and all potential confounders. We estimated the TIE by the formula (β1θ2 + β1θ3a)(a – a\*), where β1 is the exposure term in (1), θ2 is the mediator term in (2), θ3 is the exposure-mediator product in model (2), a is the observed value of the exposure and a\* is the counterfactual value of the exposure. In this case, the formula reduces to (β1θ2 + β1θ3), as exposures are dummy coded, so both a and (a—a\*) = 1. We present results in terms of crude total, adjusted total, and adjusted total indirect effects. Ninety-five percent confidence intervals for indirect effects were calculated via bootstrap with 1000 replications.46 Two-sided statistical significance was determined for all tests at α<0.05. All analyses were conducted in SAS v. 9.4 and adjusted for the complex survey design.

# Results

Key characteristics of sample participants are displayed in table 1. The median (range) age in years was 45.4 (20—85). The sample was just over half male (51.2%) and 70% Non-Hispanic White, 11.3% Non-Hispanic Black, 8.1% Mexican American, 4.4% other Hispanic, and 6.1% other race including multi-racial.

The median (IQR) plasma CRP for the entire sample was 0.17 (0.06--0.41). Approximately half the sample reported sleeping less than 6 hours per night, and 13.8% reported poor quality sleep represented by 5 or more sleep disturbances in the past month. In SES measures, reported income 0-100% and 100-199% of the federal poverty level each reflected 19% of the sample,. Twenty-six point three percent had a college degree, 30.2% had completed some college or an associate’s degree, 24.5% had a high school diploma, GED, or equivalent, 12.5% had completed 9-11th grade, and 6.6% had less than 9th grade education.

Table 2 provides one-way ANOVA comparisons in geometric mean CRP by each covariate entered into final models. Higher CRP was related to lower education, lower income, poor sleep, short sleep (<6 hours), not being physically active, female gender, Non-Hispanic Black or Mexican American race/ethnicity, older age, currently being on hormonal birth control, tobacco exposure reflected by serum cotinine 3 or more ng/mL, currently using hormone replacement therapy, and using a sleep medication (p < 0.0001 for all comparisons).

When examining whether each mediator was associated with each exposure and the outcome, we found that education was associated with short sleep (p<0.0001) but not poor sleep (p=0.33), and that income was associated with both short (p<0.0001) and poor (p=0.003) sleep. Both poor sleep (p=0.03) and short sleep (p<0.0001) were associated with higher mean CRP (see supplementary table 1 for details on these results.) Therefore, we tested for mediation of income by both short and poor sleep, and mediation of education by short sleep only.

Table 3 provides estimates of the crude and adjusted total effects, estimated with least squares linear regression. In unadjusted models estimating total effects, the arithmetic mean ratio (AMR) for 100-199% FPL was 1.21 (95% CI, 1.12—1.30), 1.21 (95% CI, 1.14—1.24) for 0-100% FPL, 1.17 (95% CI, 1.07-1.27) for some college or AA degree, 1.11 (95% CI, 1.03—1.19) for high school diploma or GED, 1.18 (95% CI, 1.07—1.29) for 9-11th grade, and 1.17 (95% CI, 1.07—1.27) for 9th grade. After adjusting the total effect models for age, gender, race/ethnicity, physical activity, birth control use, HRT use, sleep mediation use, plasma cotinine, and obesity, the AMR for 100-199% FPL was 1.11 (95% CI, 1.05—1.18), 1.17 (95% CI, 1.10—1.24) for 0-100% FPL, 1.2 (95% CI. 1.1—1.31) for some college or AA degree, 1.24 (95% CI, 1.16—1.32) for high school diploma or GED, 1.27 (95% CI, 1.17—1.39) for 9-11th grade, and 1.2 (95% CI, 1.1—1.31) for 9th grade.

Total indirect effect (TIE) estimates are also presented in table 3, adjusted for age, gender, race/ethnicity, physical activity, birth control use, HRT use, sleep mediation use, plasma cotinine, and obesity. The AMR for the TIE via poor sleep was 0.99 (95% CI, 0.99-1) for 100-199% FPL, 0.99 (95% CI, 0.98-1) for 0-100% FPL, and 0.99 (95% CI, 0.98-1) for all TIEs of education via poor sleep. The AMR for the TIE via short sleep was 1.0 (95% CI, 1—1.01) for 100-199% FPL, and 1.01 (95% CI, 1-1.01) for 0-100% FPL. TIEs were not estimated for education via short sleep as education was not associated with short sleep in the adjusted model (supplemental table 1).

# Discussion

Similarly to other studies, our study found that both lower income47-49 and lower education30,31,42,47 are associated cross-sectionally with higher c-reactive protein, indicating higher inflammatory burden in lower SES groups. Additionally, our findings reflect other observational24,25 and experimental22,23 studies showing that poor quality and short duration of sleep are associated with higher CRP. We were not, however, able to demonstrate that any portion of the effects of either education or income on plasma CRP are mediated by poor sleep quality or short sleep. This supports findings from a prospective study that restricted (<5 hours) and restless sleep do not mediate SES disparities in a number of chronic diseases.35

Our findings are potentially attributable to a number of factors. First, it is possible that the connection between SES and CRP is entirely mediated by other causal pathways, such as behavioral factors identified by previous literature. For instance, one study found that 56% of the total effect of poverty and 88% of the total effect of education on CRP was mediated by exercise, cigarette smoking, poor diet, and heavy alcohol use.31

Our finding of no mediation by sleep parameters may also be explained by measurement error. Self-reported sleep duration and quality are limited by poor recall, leading many recent studies in this area to utilize objective measurements such as polysomnography (considered the ‘gold standard’) and actigraphy.50 Objective and subjective sleep measures have been shown to have a relatively weak correlation (r=0.28 to 0.68),51 and are suggested to be used in combination for best accuracy as they measure different aspects of sleep.52 A recent simulation study showed that non-differential misclassification of a mediator biases the indirect effect towards the null much more powerfully than misclassification of the exposure.53 Therefore, the null results of our study are unable to rule out true mediation and may be the result of misclassification.

Our study is limited by a number of factors. Despite utilizing a large population-based sample, we may have had limited power to detect effects related to elevated CRP, as out of 16,654, only 188 (1.3%) had CRP between 3 and 10 mg/L, the level considered to be clinically elevated and not reflective of acute infection.17 We were limited to cross-sectional measures of SES; mediation effects may be present with respect to life course SES that are not present in current SES. Being an observational study, unmeasured confounding may have altered our results.

Despite these limitations, this study adds to the literature by being the first, to our knowledge, to formally test whether socioeconomic disparities in CRP-marked inflammatory burden are mediated by sleep duration or quality by generating indirect effect estimates. Because of the limitations of our study, we were not able to conclusively rule out mediation by sleep length and quality, and this topic warrants further investigation. Future studies examining mediation of SES health disparities by sleep parameters would be improved by prospectively examining potential mediation of life-course socioeconomic status by sleep parameters, and by including objective measurements such as polysomnography and actigraphy to avoid bias towards the null. Interventions are needed to reduce socioeconomic disparities in inflammatory burden, and the development of effective interventions necessitates the elucidation of modifiable mediators such as sleep.

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| Table 1. Descriptive statistics. | | | | | | | |
|  |  | Overall | | Short Sleep | | Poor Sleep | |
|  |  | Raw n | Weighted % | Raw n | Weighted % | Raw n | Weighted % |
| Total | | 16654 | 100.0% | 7322 | 50.2% | 2593 | 13.8% |
| Age - median (range) | | 45.4 | (20--85) | 45.2 | (20--85) | 45.1 | (20--85) |
| Plasma C-Reactive Protein (mg/L) -- median (IQR) | | 0.17 | (0.06--0.41) | 0.20 | (0.07--0.49) | 0.18 | (0.07--0.43) |
| Education | |  |  |  |  |  |  |
|  | 9-11th Grade (Includes 12th grade with no diploma) | 2629 | 12.5% | 502 | 43.3% | 1185 | 16.4% |
|  | College Graduate or above | 3135 | 26.3% | 319 | 47.7% | 1419 | 7.7% |
|  | High School Grad/GED or Equivalent | 3840 | 24.5% | 672 | 26.2% | 1830 | 7.8% |
|  | Less Than 9th Grade | 2059 | 6.6% | 356 | 93.8% | 841 | 35.1% |
|  | Some College or AA degree | 4382 | 30.2% | 739 | 22.3% | 2040 | 6.5% |
| Gender | |  |  |  |  |  |  |
|  | Female | 8073 | 51.2% | 1297 | 14.4% | 3840 | 3.7% |
|  | Male | 7999 | 48.8% | 1296 | 14.6% | 3482 | 4.3% |
| Race/ethnicity | |  |  |  |  |  |  |
|  | Mexican American | 2895 | 8.1% | 377 | 101.3% | 1166 | 29.8% |
|  | Non-Hispanic Black | 3295 | 11.3% | 851 | 33.4% | 1527 | 19.0% |
|  | Non-Hispanic White | 7779 | 70.0% | 987 | 12.4% | 3817 | 2.7% |
|  | Other Hispanic | 1371 | 4.4% | 246 | 138.8% | 519 | 54.1% |
|  | Other Race - Including Multi-Racial | 732 | 6.1% | 132 | 98.3% | 293 | 36.6% |
| Birth Control | |  |  |  |  |  |  |
|  | Missing | 1004 | 5.7% | 192 | 104.1% | 389 | 40.9% |
|  | N/A (Male) | 7999 | 48.8% | 1296 | 14.6% | 3482 | 4.3% |
|  | No | 6545 | 41.1% | 1037 | 18.1% | 3188 | 4.6% |
|  | Yes | 524 | 4.3% | 68 | 218.5% | 263 | 39.4% |
| Plasma Cotinine | |  |  |  |  |  |  |
|  | 3+ ng/mL | 4191 | 26.7% | 840 | 20.1% | 2022 | 7.1% |
|  | <3 ng/mL | 11881 | 73.3% | 1753 | 11.3% | 5300 | 2.8% |
| Hormone Replacement Therapy | | | |  |  |  |  |
|  | Missing | 1191 | 7.1% | 212 | 88.5% | 486 | 30.9% |
|  | N/A (Male) | 7999 | 48.8% | 1296 | 14.6% | 3482 | 4.3% |
|  | No | 6616 | 42.0% | 1053 | 17.8% | 3190 | 4.5% |
|  | Yes | 266 | 2.1% | 32 | 523.6% | 164 | 73.8% |
| BMI > 30 | |  |  |  |  |  |  |
|  | No | 10262 | 65.9% | 1499 | 12.0% | 4702 | 3.0% |
|  | Yes | 5810 | 34.1% | 1094 | 18.2% | 2620 | 5.9% |
| Vigorous physical activity at least 10 minutes per week | | | | | |  |  |
|  | Missing | 4442 | 32.4% | 695 | 22.9% | 3270 | 4.0% |
|  | No | 3409 | 15.9% | 594 | 40.7% | 1188 | 17.5% |
|  | Yes | 8221 | 51.7% | 1304 | 14.3% | 2864 | 5.1% |
| Income (% FPL) | |  |  |  |  |  |  |
|  | 0-100% | 4316 | 19.0% | 839 | 28.2% | 1778 | 11.6% |
|  | 100-199% | 3962 | 19.0% | 683 | 31.1% | 1794 | 10.4% |
|  | 200%+ | 7794 | 62.0% | 1071 | 14.2% | 3750 | 3.1% |
| Used sleep medication 5 or more times in last month | | | | | |  |  |
|  | Missing | 612 | 4.1% | 153 | 115.0% | 548 | 27.3% |
|  | No | 14659 | 90.2% | 2246 | 8.5% | 6013 | 2.4% |
|  | Yes | 801 | 5.7% | 194 | 81.6% | 761 | 18.1% |

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| Table 2. Geometric mean plasma c-reactive protein (CRP). | | |  |
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|  |  | Geometric meanⱡ CRP (mg/L) | P-value\* |
| Total | | 0.17 |  |
| Education | |  | <0.0001 |
|  | 9-11th Grade (Includes 12th grade with no diploma) | 0.21 |  |
|  | College Graduate or above | 0.13 |  |
|  | High School Grad/GED or Equivalent | 0.19 |  |
|  | Less Than 9th Grade | 0.20 |  |
|  | Some College or AA degree | 0.17 |  |
| Income (% FPL) | |  | <0.0001 |
|  | 0-100% | 0.19 |  |
|  | 100-199% | 0.19 |  |
|  | 200%+ | 0.16 |  |
| Vigorous physical activity at least once per week | |  | <0.0001 |
|  | Missing | 0.18 |  |
|  | No | 0.23 |  |
|  | Yes | 0.15 |  |
| Gender | |  | <0.0001 |
|  | Female | 0.20 |  |
|  | Male | 0.15 |  |
| Race/ethnicity | |  | <0.0001 |
|  | Mexican American | 0.20 |  |
|  | Non-Hispanic Black | 0.22 |  |
|  | Non-Hispanic White | 0.17 |  |
|  | Other Hispanic | 0.18 |  |
|  | Other Race - Including Multi-Racial | 0.11 |  |
| Age (yrs) | |  | <0.0001 |
|  | 20-24 | 0.12 |  |
|  | 25-29 | 0.14 |  |
|  | 30-34 | 0.15 |  |
|  | 35-39 | 0.15 |  |
|  | 40-44 | 0.17 |  |
|  | 45-49 | 0.19 |  |
|  | 50-54 | 0.18 |  |
|  | 55-59 | 0.19 |  |
|  | 60-64 | 0.22 |  |
|  | 65-69 | 0.21 |  |
|  | 70-74 | 0.23 |  |
|  | 75-79 | 0.21 |  |
|  | 80+ | 0.21 |  |
| Birth control | |  | <0.0001 |
|  | Missing | 0.18 |  |
|  | N/A (Male) | 0.15 |  |
|  | No | 0.19 |  |
|  | Yes | 0.30 |  |
| Serum Cotinine | |  | <0.0001 |
|  | 3+ ng/mL | 0.18 |  |
|  | <3 ng/mL | 0.17 |  |
| Hormone Replacement Therapy | |  | <0.0001 |
|  | Missing | 0.19 |  |
|  | N/A (Male) | 0.15 |  |
|  | No | 0.19 |  |
|  | Yes | 0.30 |  |
| Obesity (BMI > 30) | |  | <0.0001 |
|  | No | 0.12 |  |
|  | Yes | 0.34 |  |
| Poor sleep | |  | <0.0001 |
|  | No | 0.16 |  |
|  | Yes | 0.18 |  |
| Short sleep (<6 hours) | |  | <0.0001 |
|  | No | 0.17 |  |
|  | Yes | 0.20 |  |
| Used sleep medication 5 or more times in past month | |  | <0.0001 |
|  | Missing | 0.25 |  |
|  | No | 0.17 |  |
|  | Yes | 0.19 |  |
| \*Type III sum of squares F-test from ANOVA models fit using CRP transformed by the natural logarithm.  ⱡ Geometric mean values are calculated by exponentiating the regression coefficients of a linear regression model with log-transformed CRP as the response and no intercept. | | | |

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| **Table 3.** Total and indirect effects estimates of income and education on natural logarithm-transformed c-reactive protein, mediated by poor sleep and short sleep. Estimates are presented as *e* raised to the β power, and represent arithmetic mean ratios (AMRs). 95% confidence intervals (CIs) are computed for indirect effect estimates using bootstrap resampling with 1000 replications. | | | | | | | | | |
|  |  | C-Reactive Protein (natural logarithm)\* | | | | | |  |  |
|  |  |  |  |  |  | Via Poor Sleep | | Via Short Sleep | |
|  |  | Total Effect  (crude) | 95% CI | Total Effect  (adjusted) | 95% CI | Adjusted TIEǂ | 95% CI | Adjusted TIE | 95% CI |
| Income (% of FPL) (n=15,125) | | | |  |  |  |  |  |  |
|  | 0-100% | 1.21 | 1.14--1.29 | 1.17 | 1.10--1.24 | 0.99 | 0.98--1.00 | 1.01 | 1.00--1.02 |
|  | 100-199% | 1.21 | 1.12--1.30 | 1.11 | 1.05--1.18 | 0.99 | 0.99--1.00 | 1.00 | 1.00--1.01 |
|  | 200%+ | 1.00 | - | 1.00 | - | - | - | - | - |
| Education (n=15,103) | | |  |  |  |  |  |  |  |
|  | Less than 9th Grade | 1.17 | 1.07--1.27 | 1.20 | 1.10--1.31 | 0.99 | 0.98--1.00 |  |  |
|  | 9-11th Grade | 1.18 | 1.07--1.29 | 1.27 | 1.17--1.39 | 0.99 | 0.98--1.00 |  |  |
|  | High School Grad / GED | 1.11 | 1.03--1.19 | 1.24 | 1.16--1.32 | 0.99 | 0.98--1.00 |  |  |
|  | Some College or AA Degree | 1.17 | 1.07--1.27 | 1.20 | 1.10--1.31 | 0.99 | 0.98--1.00 |  |  |
|  | College Graduate or Above | 1.00 | - | 1.00 | - | - | - |  |  |
|  |  |  |  |  |  |  |  |  |  |
| \*Models fit using least squares linear regression adjusted for the survey design. Adjusted model include terms for age (continuous), gender, race/ethnicity, physical activity, birth control use, HRT use, sleep medication use, plasma cotinine, and obesity (BMI > 30). | | | | | | | | | |
| ǂ TIE = Total indirect effect | | |  |  |  |  |  |  |  |

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| **Supplementary table 1.** Results of examining whether each hypothesized mediator was associated with each exposure and the outcome. | | | | | | | | |
|  | Short Sleep | | | | Poor Sleep | | | |
|  | Χ2 |  | DF | P-value | Χ2 |  | DF | P-value |
| Education | 78.7 |  | 4 | <0.0001 | 4.6 |  | 4 | 0.33 |
| Income | 59.2 |  | 2 | <0.0001 | 11.6 |  | 2 | 0.003 |
| C-reactive protein | 6.4 | \* | 1 | 0.014 | 5.1 | \* | 1 | 0.028 |
|  |  |  |  |  |  |  |  |  |
| \*Values are F statistic, rather than X2. | | | |  |  |  |  |  |

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