

## A Twin Study of Sleep Duration and Body Mass Index

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**Study Objective:** To determine the relative importance of genetic and environmental contributions to the association between sleep duration and body mass index (BMI).

**Methods:** Twins from the University of Washington Twin Registry, a community-based sample of U.S. twins, provided self-reported height and weight for BMI calculation and habitual sleep duration. A generalized estimating equation model evaluated the overall and within twin pair effects of sleep duration on BMI with and without stratification by twin zygosity. A structural equation model was used to assess genetic and non-genetic contributions to BMI and sleep duration.

**Results:** The study sample included 1,224 twins comprised of 423 monozygotic, 143 dizygotic, and 46 indeterminate pairs. The mean age was 36.9 years; 69% were female. A multivariate adjusted analysis of all twins revealed an elevated mean BMI (26.0 kg/m<sup>2</sup>) in short sleeping twins (< 7 h/night) compared to twins sleeping 7–8.9 h/night (BMI 24.8 kg/m<sup>2</sup>;  $p < 0.01$ ). The within-twin pair analysis revealed similar results, with the short sleeping twins having a mean BMI of 25.8 kg/m<sup>2</sup> compared to 24.9 kg/m<sup>2</sup> for the 7–8.9 h/night sleep duration

group ( $p = 0.02$ ). When restricted to monozygotic twins, the within-twin pair analysis continued to reveal an elevated BMI in the short sleeping twins (25.7 kg/m<sup>2</sup>) compared to the 7–8.9 h/night reference group (24.7 kg/m<sup>2</sup>;  $p = 0.02$ ). No differences in mean BMI were observed between the 7–8.9 h/night reference group twins and longer sleeping twins ( $\geq 9$  h/night) in the analysis of all twins, the overall within-twin pair analysis, or the within-twin pair analysis stratified by zygosity. The heritability of sleep duration was 0.31 ( $p = 0.08$ ) and BMI 0.76 ( $p < 0.01$ ). Bivariate genetic analysis revealed little evidence of shared genetics between sleep duration and BMI ( $p = 0.28$ ).

**Conclusions:** Short sleep was associated with elevated BMI following careful adjustment for genetics and shared environment. These findings point toward an environmental cause of the relationship between sleep duration and BMI.

**Keywords:** Sleep duration, obesity, twins, monozygotic, dizygotic, body mass index

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The advent of artificial lighting, shift work, television, the internet, and a 24-hour economy have all curtailed sleep times. As a result, sleep deprivation has reached epidemic proportions in our society, with ~25% of the population regularly obtaining insufficient sleep to maintain normal alertness.<sup>1,2</sup> Although the optimal amount of sleep for humans is unknown, we now sleep 1.5 h/night less than we did in 1910.<sup>3</sup> In the 2002 National Sleep Foundation Sleep in America Poll, 39% of adults reported sleeping < 7 h/night on weeknights.<sup>4</sup> Meanwhile, human sleep need remains unchanged. As sleep duration has dropped, rates of obesity have increased, with the most recent National Health and Nutrition Examination Survey reporting that 33.3% of adult men and 35.3% of adult women are obese.<sup>5</sup>

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Research suggests chronically reduced sleep times are associated with obesity.<sup>6-11</sup> Experimental studies in humans show that sleep curtailment influences the neuroendocrine control of appetite in healthy individuals.<sup>12</sup> Population-based studies demonstrate a significant U-shaped non-linear relationship between nightly sleep duration and body mass index (BMI).<sup>13,14</sup> Compared to those sleeping 7–8 h/night, individuals sleeping

### BRIEF SUMMARY

**Current Knowledge/Study Rationale:** Twin study methodologies were used to determine the relative importance of genetic and environmental contributions to the association between sleep duration and body mass index (BMI).

**Study Impact:** An association was observed between short sleep duration and elevated BMI in a community based sample of US twins after accounting for familial factors such as genetics and shared environment. This supports the environmental hypothesis that voluntary changes to habitual sleep duration influences BMI independent of familial factors.

$\leq 6$  h are at greater risk of being obese.<sup>14</sup> Prospective family and cohort studies have found short sleep duration is associated with the development of obesity over time.<sup>15-17</sup> Although the relationship between sleep duration and BMI may be caused by environmental influences such as voluntary sleep restriction, many measures of sleep are heritable, raising the possibility that genetic factors are central to this association.<sup>18-23</sup> To date, no studies have accounted for shared genetic and environmental factors when considering the relationship between sleep duration and BMI.

Twins are identical in age and, if reared together, are typically well-matched for shared family background and numer-

ous childhood/adolescent exposures. Because twins tend to be quite similar on variables that differ among unrelated individuals, studying them allows detection of subtle environmental effects, such as the effect of chronic partial sleep restriction on body weight. We therefore conducted a twin study to account for the potential shared genetic and environmental contributions to habitual sleep duration and obesity. Our goals were to: (1) determine if sleep duration was associated with BMI in our twin sample and (2) examine if the association between sleep duration and BMI was confounded by familial factors such as genetics and shared environment. If we observed an association following adjustment for between-twin pair effects, this finding would support the environmental hypothesis that voluntary changes to habitual sleep duration influences BMI independent of familial factors.

## METHODS

### Participants

The University of Washington Twin Registry is a community-based sample of twins constructed using data from the Washington State Department of Licensing. The minimum age for participation is 18 years. As of September 2008, the Registry consisted of 2,638 dizygotic and monozygotic pairs with information on ~80 new individual twins collected weekly. Zygosity is determined using previously validated self-report methods that are correct  $\geq 95\%$  of the time.<sup>24,25</sup> In 2006, a Health Survey was mailed to 4,407 twins that included questions on sleep. The data collection procedures were approved by the University of Washington Institutional Review Board and the State of Washington Attorney General's office.

### Sleep Duration, BMI, and Covariates

#### Sleep Duration

Habitual sleep duration was obtained from responses to the question, "On average, how long do you sleep per night?" reported in hours and minutes. We categorized sleep duration into 3 groups. Normal sleep duration was considered 7–8.9 h. This range was chosen because it encompassed the physiologically normal sleep fraction in humans,<sup>26,27</sup> represented normal sleep as defined by the National Sleep Foundation,<sup>28</sup> and contained the sleep duration considered normal in previous studies of sleep and metabolism.<sup>14,29,30</sup> We classified sleep duration of  $< 7$  h/night as short sleep and  $\geq 9$  h as long sleep.

#### Body Mass Index

Self-reported height and weight were obtained from the following questions: "How tall are you without your shoes," and "How much do you weigh without clothes or shoes." With these data we calculated BMI as  $\text{kg}/\text{m}^2$ . For analytic purposes BMI was divided into 3 categories: normal weight (BMI  $< 25$ ), overweight (BMI between 25 and 29.9), and obesity (BMI  $\geq 30$ ).<sup>31</sup>

#### Sociodemographics

Age, gender, and race were self-reported. Race was dichotomized into white and non-white (American Indian or Alaska Native, Native Hawaiian or Pacific Islander, Asian, Black or

African American, or other) categories. Cohabitation status was ascertained from the question, "What is your current marital status?" Those considered to be cohabiting endorsed being married or living with a partner. All other responses (single and never married, divorced, widowed, or separated) were considered non-cohabiting living arrangements. Number of children living in the same household was obtained from the question, "How many children (including adopted and foster children) are currently living with you?" Categories included none, 1–2 children, and  $\geq 3$  children.

#### Health Habits

Smoking history was ascertained from the question, "Do you now smoke cigarettes every day, some days, or not at all?" Any cigarette consumption was considered a positive history. Alcohol use was obtained from the question, "How many drinks of alcohol do you have on a typical day when you are drinking?" Drinking categories included zero, 1 or 2 drinks, 3 or 4 drinks, or  $\geq 5$  drinks.

#### Chronic Disease

Twins were asked, "Has a medical doctor, dentist, or other health care professional ever diagnosed you with type I or II diabetes, heart disease (heart attack, angina, bypass surgery) or stroke?" An affirmative response to any of these diseases was considered a positive history of chronic disease.

#### Statistical Methods

Based on data from the survey, we excluded twins who were raised apart because of the influences of separate environment on family background. We then calculated means and frequency distributions for demographic and health-related variables according to sleep duration. Next, we conducted a formal statistical analysis of the association of sleep duration with BMI in 2 ways. First, we treated the twins as individuals while accounting for the correlated data structure using generalized estimating equations. Second, we extended the generalized estimating equations model to explicitly model within- and between-pair effects of sleep duration on BMI; the within-pair analysis is of particular interest, since this controls for genetic and common environmental influences shared by twins within a pair. Third, we repeated our within and between analysis after stratification by twin zygosity. The analysis of within-pair differences using monozygotic pairs provides a way to completely control for shared genetic influences.

We used a generalized estimating equations linear regression model with sleep duration as the exposure of interest and BMI as the outcome of interest. Indicator variables were defined for the 3 categories of sleep duration ( $< 7$  h, 7–8.9 h, and  $\geq 9$  h); twins in the 7–8.9 h group were treated as the reference level. BMI was maintained as a continuous variable. Statistical significance for sleep duration was assessed using 1 degree of freedom  $\chi^2$  tests to compare the reference level (7–8.9 h) to shorter and longer sleep duration. For expository purposes, we present effects as the estimated mean BMI for each category of sleep duration; these predicted least square mean values were derived from the fitted model along with 95% confidence intervals. We examined results both before and after adjustment for covariates; however, unadjusted and adjusted estimates were similar, so we present adjusted estimates only.

Potential covariates were selected based on existing publications on the association between habitual sleep duration and BMI.<sup>11,13-15,32</sup> We included: gender, age, race, smoking, alcohol use, education level, income, hours worked per week, depression, exercise, cohabitation status, number of children living in the household, and the presence of chronic disease. Each potential covariate was assessed for potential confounding by adding the covariate to the unadjusted model between sleep duration and BMI. Factors were selected for inclusion into a final adjusted model based on both a priori considerations and the change in the sleep duration parameters compared with the unadjusted model. Our final model adjusted for demographics (age, gender, race), health habits (smoking, alcohol history), sociodemographics (cohabitation status, and number of children living in the household), and the presence of chronic disease.

We used structural equation modeling to estimate the univariate genetic and non-genetic contribution to BMI and sleep duration.<sup>33</sup> First, we used intraclass correlation coefficients to estimate the within-pair correlation for BMI and sleep duration separately in monozygotic and dizygotic pairs. Next, a model was fitted to the raw data to estimate the component of phenotypic variance that is due to additive genetic (A), common environmental (C), and unique environmental (E) components. The method builds on the assumption that monozygotic twins share 100% of their genetics and dizygotic twins share, on average, only 50%. Common environmental factors are assumed to be shared 100% by both monozygotic and dizygotic pairs. Unique environmental effects reflect experiences that are not shared by both members of a twin pair. The significance of the additive genetic effect was determined by a likelihood ratio  $\chi^2$  test comparing the full ACE model to a reduced model that did not include additive genetics (CE).

Bivariate structural equation modeling was used to test for the presence of shared genetic or environmental influences on BMI and sleep duration. The model started with a full Cholesky decomposition that specifies a general multivariate covariance structure that allows for both shared and specific influences on BMI and sleep duration. Reduced models were then fit after removing shared influences. We compared the fit of reduced models to the full ACE model using likelihood ratio  $\chi^2$  tests. Twin pairs of indeterminate zygosity were excluded from all structural equation modeling.

## RESULTS

The Health Survey was completed and returned by 2,402 twins, comprising 880 twin pairs (1,760 twins) and 642 individual twins. The 1,224 twins with complete data included in these analyses comprised 612 twin pairs; 423 monozygotic, 143 dizygotic, and 46 indeterminate zygosity. The sample was 69% female and 92% Caucasian; mean age was 36.9 (SD = 15.0) years. As shown in **Table 1**, the majority of twins (66%) slept 7–8.9 h/night, with 25% sleeping < 7 h and 9% sleeping  $\geq$  9 h/night. Gender, age, and race were similar in the 3 sleep duration groups. Shorter sleeping twins endorsed more smoking and drinking, were less likely to cohabit and more likely to have chronic diseases, and had more children living in the household than the longer sleeping twins. Fifty-eight percent of the sample was normal weight, 25% was overweight, and 17% was obese.

**Table 1**—Demographic and health variables according to sleep duration

	Twin Sample (n = 1,224)	Sleep duration		
		< 7 hours (n = 306)	7–8.9 hours (n = 807)	$\geq$ 9 hours (n = 111)
<b>Demographic</b>				
Age, mean years	36.9 (15.0)	38.6 (14.4)	36.3 (14.9)	36.4 (17.3)
Female, %	69	64	70	72
White, % <sup>†</sup>	92	89	94	91
Cohabiting <sup>‡</sup> , %	51	45	52	59
Children living in home, %				
None	73	70	73	82
1–2	22	23	22	15
$\geq$ 3	5	6	5	3
<b>Health</b>				
Smoker, %	16	23	14	12
Alcoholic drinks/day <sup>§</sup> , %				
None	16	15	16	20
1–2	58	56	60	53
3–4	17	18	17	16
$\geq$ 5	9	12	7	10
Chronic disease <sup>¶</sup> , %	5	8	3	8

<sup>†</sup>Race was defined as white or nonwhite; <sup>‡</sup>Cohabitation included twins that were married or living with a partner; <sup>§</sup>Drinks of alcoholic beverages consumed on a typical day when the twin was drinking; <sup>¶</sup>Chronic disease included twins with any of the following: type I or II diabetes mellitus, stroke, or heart disease (e.g., heart attack, angina, bypass surgery)

## Twins as Individuals Analysis

Twins reporting a shorter sleep time had an elevated mean BMI (26.0 kg/m<sup>2</sup>) compared to the reference sleep duration twin group (24.8 kg/m<sup>2</sup>;  $p < 0.01$ ). No BMI difference was observed between the longer sleeping and reference group twins (**Table 2**).

## Within-Twin Pair Analysis

A total of 245 twin pairs were discordant for sleep duration and thus informative to the analysis. Similar to the twins as individuals analysis, the shorter sleeping twins had a higher mean BMI (25.8 kg/m<sup>2</sup>) than the reference group (24.9 kg/m<sup>2</sup>;  $p = 0.02$ ). No BMI difference was observed between the longer sleeping and reference group twins (**Table 2**). When stratifying the within-twin pair analysis sample by zygosity status, we found similar results in the monozygotic pairs, with an elevated mean BMI in the shorter sleeping twins (25.7 kg/m<sup>2</sup>) compared with the reference group (24.7 kg/m<sup>2</sup>;  $p = 0.02$ ), with no BMI difference between the longer sleeping and reference group twins. No similar findings were observed for the dizygotic pairs (**Table 3**).

## Heritability of Sleep Duration and Body Mass Index

For sleep duration, the intraclass correlation coefficient was twice as large in monozygotic twins as in dizygotic twins, revealing a heritability estimate of 0.31 ( $p = 0.08$ ). For BMI, the

**Table 2**—Adjusted<sup>†</sup> mean body mass index and 95% confidence interval according to sleep duration

Sleep Duration, hours	Overall			Within-pair*		
	Mean BMI, kg/m <sup>2</sup>	(95% CI)	p-value <sup>‡</sup>	Mean BMI, kg/m <sup>2</sup>	(95% CI)	p-value <sup>‡</sup>
< 7	26.0	(25.2–26.7)	< 0.01	25.8	(25.1–26.5)	0.02
7–8.9	24.8	(24.4–25.2)	ref	24.9	(24.5–25.2)	ref
≥ 9	25.4	(24.2–26.5)	0.32	25.3	(24.2–26.4)	0.44

<sup>†</sup>Adjusted for age, gender, race, smoking history, alcohol consumption, cohabitation status, number of children living in the household, and chronic disease; \*Within-pair analyses based on 245 pairs discordant for sleep duration category; <sup>‡</sup>Referent category for  $\chi^2$  tests was 7–8.9 h sleep duration; BMI, body mass index; CI, confidence interval

**Table 3**—Adjusted<sup>†</sup> within-pair BMI and 95% CI according to sleep duration and zygosity

Sleep Duration, hours	Monozygotic pairs (n = 423 pairs, 167 pairs discordant for sleep duration)			Dizygotic pairs (n = 143 pairs, 57 pairs discordant for sleep duration)		
	Mean BMI, kg/m <sup>2</sup>	(95% CI)	p-value*	Mean BMI, kg/m <sup>2</sup>	(95% CI)	p-value*
< 7	25.7	(24.8–26.5)	0.02	25.8	(24.2–27.5)	0.68
7–8.9	24.7	(24.2–25.1)	ref	25.4	(24.4–26.4)	ref
≥ 9	24.7	(23.9–25.6)	0.84	27.4	(24.1–30.8)	0.28

<sup>†</sup>Adjusted for age, gender, race, smoking history, alcohol consumption, cohabitation status, number of children living in the household, and chronic disease; \*Referent category for  $\chi^2$  tests was 7–8.9 hours sleep duration; BMI, body mass index; CI, confidence interval

correlation coefficients were high for both monozygotic and dizygotic twins, but higher for monozygotic twins resulting in a heritability estimate of 0.76 ( $p < 0.01$ ; **Table 4**).

### Bivariate Genetic Analysis

The bivariate analysis partitioned the covariation between BMI and sleep duration into shared additive genetic components (A), shared common environmental components (C), and unique environmental components (E). As shown in **Table 5**, the lack of significant findings when comparing reduced models to the full ACE model revealed limited evidence of shared genetic ( $p = 0.28$ ) or common environmental components ( $p = 0.13$ ) between sleep duration and BMI.

## CONCLUSIONS

We observed a significant relationship between short habitual sleep duration and elevated mean BMI in a community-based sample of U.S. twins. This relationship was robust and observed both among individual twins and within twin pairs after adjustment for confounding factors. The within-pair analyses allow unique insights into the relationship between sleep duration and BMI, as they account for the potential confounding influence of familial factors such as genetics and shared environment (e.g., in utero exposures, early life diet, and living conditions). The presence of this within-pair association supports the environmental hypothesis regarding the relationship between sleep duration and BMI, namely, that voluntary curtailment of sleep, and not familial factors, drive the association.

Our findings suggest a U-shaped pattern between habitual sleep duration and BMI. This is consistent with published reports

indicating increased BMI is related to decreased sleep time, with attenuation of the effect at longer sleep durations.<sup>13–15</sup> The association in our twin sample was observed between the short (< 7 h) and normal (8–8.9 h) sleeping twins. Differences in BMI were not evident between the long (≥ 9 h) and normal sleeping twins. Of note, the literature regarding the relationship between longer sleep and BMI is conflicting; some studies show an increase in BMI with longer sleep,<sup>13,14,16</sup> while others show a decrease,<sup>15</sup> and still others, similar to our results, find no effect.<sup>11</sup>

Our results are consistent with The Quebec Family Study, another genetically informative investigation of the relationship between sleep duration and BMI. This study investigated prospective weight gain and obesity development in 276 individuals from French-Canadian families in the greater Quebec City area.<sup>16</sup> They found elevated weight gain and risk of developing obesity in both short (5–6 h) and long (9–10 h) sleepers compared to normal (7–8 h) sleepers. Similar to our overall twin sample analysis, their study design accounts for familial factors, but unlike our study, they lacked the ability to separate out effects within and between families, and therefore they could not investigate shared genetic vulnerability between BMI and sleep duration in bivariate analyses. Our study adds to their findings in other important ways as well. Because ours is a twin study, we were able to assess within-twin pair effects, allowing assessment of the strength of the association while accounting for familial factors such as genetics and shared environment. Also, our sample is more than 4 times as large as the Quebec Family Study, providing additional power to detect associations.

We observed a modest heritability of 31% for sleep duration, consistent with previous reports.<sup>34,35</sup> The marginal significance of our sleep duration heritability estimate indicates that we can-



**Table 4**—Twin correlation and univariate structural equation models for BMI and sleep duration

Characteristic	Intraclass correlation coefficient		$h^{2†}$	(95% C I)	$c^{2†}$	(95% C I)
	Monozygotic	Dizygotic				
BMI	0.76	0.47	0.76*	(0.54, 0.80)	0.00	(0.00, 0.22)
Sleep duration	0.38	0.19	0.31†	(0.00, 0.43)	0.04	(0.00, 0.35)

$h^2$  and  $c^2$  are estimates of the proportion of additive genetic and common environmental components of variance, respectively, calculated for the full ACE model; \* $p < 0.01$ ; † $p = 0.08$ ; CI, confidence interval

not definitively establish if familial clustering is due to genetics or common environment. Our bivariate analysis revealed limited evidence of shared genetic or common environmental effects for sleep duration and BMI. Future twin studies with a larger sample, and objective measurement of sleep duration with actigraphy would help further establish heritability estimates and shared genetic effects for sleep duration and associated phenotypes.

A growing body of experimental and epidemiological evidence suggests that deviations in sleep duration from physiological sleep need alters metabolism in a manner that predisposes to weight gain.<sup>12,13</sup> Hypothalamic-pituitary functions regulating appetite, energy balance, and metabolism are tightly linked to mechanisms controlling circadian rhythms and sleep regulatory processes.<sup>6,36</sup> Leptin, an adipocyte-derived hormone that regulates body adiposity,<sup>37</sup> and ghrelin, an orexigenic peptide hormone secreted primarily by the stomach,<sup>37,38</sup> play a major role in appetite control, food intake, and weight regulation, and are central to the sleep duration – BMI relationship. Sleep restriction, by decreasing leptin and increasing ghrelin, may increase appetite and hunger, particularly for high-fat, high-carbohydrate meals.<sup>12</sup> Sleep and circadian factors cause a nocturnal peak in leptin levels,<sup>39</sup> and sleep restriction dampens this peak, presumably by reducing nocturnal appetite suppression.<sup>40,41</sup> A crossover study of short-term partial sleep deprivation in 12 healthy young men revealed significant reductions in leptin and increases in ghrelin levels,<sup>12</sup> a finding replicated in a large population based study using self-reported sleep durations and single hormone measurements.<sup>13</sup> Ghrelin levels and hunger increase following a single night of total sleep deprivation.<sup>42</sup> Leptin and ghrelin profiles similar to those seen in obese, sleep-restricted individuals can follow weight loss,<sup>13,43</sup> suggesting these changes contribute to, rather than compensate for, the association between habitual sleep restriction and BMI.

The mechanism for the relationship between leptin and ghrelin concentrations and sleep duration is unknown. Some studies have found that sleep loss is associated with increased sympathetic nervous system outflow<sup>44</sup> and leptin release was inhibited by sympathetic nervous system activity.<sup>45</sup> Thus, decreased leptin levels in the context of habitual sleep curtailment may result from this increased sympathetic outflow.<sup>12</sup> Increased cardiac sympathovagal balance has been observed following sleep deprivation.<sup>46</sup> This could reflect decreased vagal activity and account for the increased ghrelin levels, as the vagus negatively influences ghrelin secretion.<sup>12,46</sup> Other factors, such as increases in the lipogenic hormone cortisol following sleep curtailment,<sup>46</sup> may also

**Table 5**—Bivariate structural equation model fitting for BMI and sleep duration

Shared component <sup>†</sup>	$\chi^2$	df	p value
ACE	–	–	–
CE	1.17	1	0.28
AE	2.29	1	0.13
AC	2.17	1	0.14
A	3.96	2	0.14
C	2.67	2	0.26
E	2.86	2	0.24

<sup>†</sup>ACE refers to a model that includes shared additive genetics (A), shared common environment (C), and unique environment (E); CE includes only shared common and unique environment; AE includes only shared additive genetics and unique environment, AC only includes shared additive genetics and shared common environment; A includes only shared additive genetics; C includes only shared common environment; E includes only unique environment; all reduced models are compared to ACE

explain the association between sleep duration and BMI. Sleep deprivation reduces glucose tolerance and increases sympathetic tone, both of which are associated with obesity.<sup>46,47</sup> Growth hormone secretion, which is important for maintaining lipolysis, is dependent on sleep.<sup>48</sup> Obesity could also be facilitated by activation of inflammatory pathways by shortened sleep length.<sup>30</sup> Further research is needed to establish causation and describe the physiology of the sleep duration – BMI relationship.

Many subjective and objective measures of sleep are heritable, leading to the hypothesis that sleep length required for optimal alertness is genetically based.<sup>18-23</sup> Sleep times in the general population follow a normal distribution. In conditions of time and environmental isolation, the physiologically normal “sleep fraction” in humans was found to be between 29% and 33% of the sleep-wake cycle, or 7 to 7.9 hours.<sup>26,27</sup> Twin studies of sleep indicate that subjective reports of sleep including daytime napping, habitual bedtime and waketime, sleep duration, and subjective sleep quality exhibit strong heritability.<sup>20,34,35</sup> Polysomnography in twins shows that body movements, stage 2, slow wave sleep, and REM density are all largely genetically determined.<sup>19,49-51</sup> Polymorphisms in circadian clock genes may be important determinants of sleep time, and animal studies have revealed that sleep amount has a high genetic load and may be controlled by a few genes.<sup>52</sup> Taken together, these investigations highlight the value of using twins in studies on the

metabolic effects of sleep duration. The genetic similarities of twins account for, in large part, potential confounding familial factors such as genetics and shared environment, which allow the detection of subtle environmental effects that would otherwise be obscured.

This study has several limitations. First, because our twins were predominantly younger adult Caucasian women, these findings should be applied to the general population with caution. To our advantage, however, our sample was derived from the community and not from a clinical population seeking health care. Second, self-reported sleep duration and BMI are commonly used in observational studies but can be problematic.<sup>11,14,15</sup> Self-reported sleep duration approximates objective measures of sleep length,<sup>53,54</sup> though recent studies suggest it may be biased.<sup>55</sup> Body mass index based on self-reported height and weight may be inaccurate, though validation studies indicate errors are unlikely to affect conclusions about associations between BMI and health variables.<sup>56-58</sup> Third, our study is cross-sectional; therefore, inferences regarding causality are inappropriate. A final concern is our ability to account for all potential confounders that can influence sleep duration and BMI. We adjusted for many demographic and health characteristics linked to sleep duration and BMI and our within-pair analysis intrinsically controlled for genetic and common environmental factors. Despite these measures, it is possible that residual confounding exists, perhaps due to our inability to adjust for factors such as depression and medications. However studies of sleep duration and BMI in pediatric populations suggest that residual confounders may have little effect since confounding comorbidities are uncommon in children, yet pediatric studies demonstrate the same association between sleep duration and BMI observed in adults.<sup>8,10</sup>

In conclusion, we found short sleep duration was associated with elevated BMI in a unique community-based sample of adult twins, both overall and within twin pairs, before and after adjusting for potential confounding variables. Our findings imply the association is due to unique environmental factors, such as self-imposed sleep restriction, and contribute to a growing body of evidence of a link between sleep curtailment and obesity. Future efforts should derive sleep duration from sleep diaries or actigraphy, obtain objective measures of height and weight, and carefully collect data on covariates. Of importance, interventional and prospective research that demonstrates habitual sleep curtailment increases BMI could have major public health implications, considering obesity heightens the risk for cardiovascular disease and diabetes,<sup>11,14,30,59-62</sup> and up to one-third of the population fails to sleep enough to maintain physiological homeostasis.<sup>4</sup> The potential for intervention studies, focusing on sleep prolongation as a novel approach to lower weight, is an area that warrants exploration.

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## DISCLOSURE STATEMENT

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