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Original Article

Objectively measured sleep and body mass index: a prospective bidirectional study in middle-aged and older adults

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ABSTRACT

Background: In recent years, short sleep has been increasingly recognized as a risk factor for obesity. However, current evidence has so far been limited to cross-sectional studies or longitudinal studies using self-reported sleep. Therefore, we explored the directionality of the association between objectively measured sleep and body mass index (BMI).

Methods: The study consists of 1031 participants from the general population (52% women, 45–91 years at baseline). Sleep, BMI and waist circumference (WC) were measured twice across a follow-up of six years. BMI and WC were measured at the research center. Total sleep time (TST, hrs), sleep onset latency (SOL, min), sleep efficiency (SE, %) and wake after sleep onset (WASO, min) were estimated by a wrist-worn actigraph. In addition, cross-sectional and longitudinal associations in both directions were explored.

Results: An hour shorter TST was cross-sectionally associated with approximately 0.5 kg/m^2 higher BMI. Longitudinally, longer TST and higher SE were associated with lower BMI ($\beta_{TST} = -0.75$, 95% CI: −1.08, −0.42; $\beta_{SE} = -0.04$, 95% CI: −0.08, −0.01). Conversely, one kg/m^2 higher BMI was prospectively associated with 0.02 h shorter TST (95% CI: −0.03, −0.01), and this association was more pronounced over time. Results from analyses with WC were in line with those of BMI.

Conclusions: This is the first study to explore bidirectionality in the association between objectively measured sleep and BMI in a large population of middle-aged and older adults. Indices of poor sleep were associated with higher and less stable BMI across time. Conversely, a high BMI was associated with a decrease in sleep duration. This confirms that the relation between sleep and body size is bidirectional, and changes in either sleep or BMI are likely to co-occur with changes in health through multiple pathways.

1. Introduction

Sleep has been identified as a potentially modifiable factor related to mental and physical health [1,2]. Short sleep duration has been associated with higher body weight and obesity [3]. This has given rise to the idea that chronic sleep curtailment contributes to the developing obesity epidemic [4]. Alternately, there is little evidence for a temporal decline in sleep duration over the past 50 years [5].

Numerous observational studies examining the association between sleep duration and adiposity have concluded that short sleep is associated with an increased risk of obesity, defined as having a body mass index (BMI) greater or equal to 30 kg/m^2 [3,6–10], however, several studies found no association [11–14]. Meta-

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analyses, however, observed an inverse cross-sectional association of sleep duration with BMI and waist circumference (WC), a measure of central adiposity [15,16]. Based on these findings, the hypothesis that short and disturbed sleep has a direct influence on energy metabolism leading to weight gain has been postulated [17]. However, studies assessing the association between sleep and obesity have important methodological limitations. First, studies have mostly been cross-sectional, not allowing exploration of the temporality of the association [3,16]. Second, prospective studies have relied on self-reported measures, which are prone to information and recall bias [11,18].

Adiposity might also influence sleep [19]. Nevertheless, most experimental studies have examined the hypothesis that high BMI reduces sleep duration and quality over time [20-22]. The only study that explored bidirectionality in the association between sleep and adiposity measured self-reported sleep and concluded that a higher BMI predicts a minor decrease in sleep duration over time, but not vice versa [14].

To overcome these limitations, prospective studies using repeatedly measured objective sleep and body composition are required. We evaluated the direction of the association of actigraphic sleep patterns with BMI and WC, in a population-based prospective cohort of middle-aged and older persons. Objective measures of sleep, BMI and WC were assessed twice over a follow-up of six years.

2. Methods

2.1. Study population

This study was embedded in the Rotterdam Study, an ongoing prospective population-based cohort in the Netherlands. The cohort was initially defined in 1990 (RS-I) and expanded in 2000 (RS-II) and 2005 (RS-III). In the first two cohorts, all inhabitants aged 55 years and older who were living in the Ommoord district of Rotterdam were invited to participate [23]. For RS-III, all inhabitants aged 45 years and older were invited. In the current study, we used data from participants attending the fourth and fifth visit of the original cohort (RS-I-4 and RS-I-5), participants attending the second and third examination of the extended cohort (RS-II-2 and RS-II-3) and participants attending the first and second examination of the third cohort (RS-III-1 and RS-III-2). Participants undergo extensive follow-up examinations approximately every five years [24,25].

For the baseline of our study (T1: December 2004 to April 2007), 2632 participants were invited to participate in the actigraphy study, 2063 (78%) agreed to participate [26,27]. Due to technical issues (n = 125), valid data was available for 1938 participants at baseline. Of these 1938 individuals, 1431 participants that visited the research center at the next wave of measurements were invited for a follow-up measurement (T2: March 2009 to June 2014). Valid sleep data on at least four 24 h-periods and anthropometric data in both waves was available for 1031 individuals of BMI and for 999 individuals of WC. There were no exclusion criteria besides being able to understand the instructions for this study. All subjects gave written informed consent, and the study protocol was approved by the medical ethics committee according to the Population Study Act Rotterdam Study, executed by the Ministry of Health, Welfare and Sport.

2.2. Measurement of sleep

At baseline, all participants wore an actigraph around the non-dominant wrist (Actiwatch model AW4; Cambridge Technology, Cambridge, UK) for seven consecutive days and nights. The device had to be removed for water-based activities. At follow-up, participants wore either the Actiwatch (n = 592), or a GeneActiv triaxial accelerometer (Activinsights Ltd, Kimbolton, Cambridgeshire, UK) (n = 439). Recordings were sampled at 32 Hz (Actiwatch) or 50 Hz (GeneActiv), and were averaged into a score for each 30-s interval, taking into account weighted values of previous and following epochs. To ensure comparability between the estimates of the two devices, we used a validated algorithm to convert the triaxial GeneActiv to one-dimensional 30s epoch data (using the z-axis), that was thereafter calibrated to Actiwatch counts using Passing-Bablok regression [28].

To estimate sleep parameters, we used an algorithm validated against polysomnography at the highest sensitivity (sleep threshold <20 counts) [18,29]. Sleep diaries were used to determine bedtime, wake-time and get-up time. A night's data was considered invalid if a recording had failed due to technical issues, the participant had discontinued wearing the actigraph, or if the information on bedtime and get-up time from the sleep diary, needed for the algorithm to detect sleep, were invalid or missing. The assumed sleep period was defined as the time between sleep onset and final wake-time estimated by the algorithm [18,29,30], and the following sleep parameters were calculated: (1) Total sleep time ((TST), hours): the sum of the number of epochs in the assumed sleep period scored as sleep, multiplied by the epoch length; (2) Sleep onset latency ((SOL), minutes): time between bed time according to the sleep diary and the estimated sleep onset; (3) Sleep efficiency ((SE), %): ratio of TST to time in bed (time between bedtime and wake-time) multiplied by 100; and (4) Wake after sleep onset ((WASO), minutes), defined as the number of epochs within the assumed sleep period scored as wake multiplied by the epoch length.

2.3. Anthropometric measurements

Height and weight were measured by trained staff in the research center with the participants standing without shoes and heavy outer garments on a calibrated scale. BMI was calculated as weight divided by height squared (kg/m^2). WC (cm) was measured at the level midway between the lower rib margin and the iliac crest, with participants in standing position and breathing out gently.

2.4. Measurement of covariates

Education was assessed in line with the international standard classification of education [30] and grouped into primary education, lower education, intermediate education and higher education. Employment status was used as a binary variable (employed/unemployed). Smoking was categorized as: current, former and never. Physical activity was assessed with the validated Longitudinal Aging Study Amsterdam (LASA) Physical Activity Questionnaire (LAPAQ) [31], including questions on housekeeping activities, walking, cycling, sports and gardening. Time spent in these activities was combined and expressed in metabolic equivalent of task (MET)·hours/week. Alcohol consumption was assessed by interview and z-standardized for analyses. The presence of cardiovascular disease, diabetes and cancer was determined using medical records. We defined a binary variable for the presence of any of these chronic diseases. Depressive symptoms were assessed with the Center for Epidemiologic Studies Depression (CES-D) scale [32], excluding the question on restless sleep in the score. Frequency of napping was defined as the number of days the participant had napped during the actigraphy assessment, as reported in the sleep diary [26]. As a proxy of sleep disordered breathing (SDB), one item of the Pittsburgh Sleep Quality Index (PSQI) [33] was used to assess the frequency of respiratory pauses during sleep.

2.5. Statistical analyses

Missing values on covariates were less than 10%, except for the frequency of SDB at T1 (19%) and the frequency of SDB at T2 (17.9%). We imputed missing data using fully conditional specification multiple imputation (m = 20 imputations). Statistical analyses were performed on each imputed data set, and results were pooled [34].

Cross-sectional associations between sleep parameters (TST, SE, SOL and WASO) and BMI were tested using linear regression at baseline and at follow-up (when two different actigraphy devices were used) in a model correcting for several covariates (see tables). The decision to include covariates was based on previous literature [27,35,36]. Additionally, the effect of adding each of the covariates in the models was examined by computing the percentage of change in the effect estimate for the independent variable after including the specific covariate.

We created sex and age adjusted linear mixed models (additionally adjusted for actigraphy device at follow-up) and linear mixed models corrected for all covariates as mentioned above to examine whether sleep parameters were associated with (changes in) BMI across time, and the converse, whether BMI was associated with (changes in) sleep parameters across time. All models included (1) the time between the baseline and follow-up measurement of the outcome variable in years; (2) the average of the determinant across the two measurements (eg, $(TST_{T2}+TST_{T1})/2$ or $(BMI_{T2}+BMI_{T1})/2$); (3) the yearly change in the determinant (eg, $\Delta TST=(TST_{T2}-TST_{T1})$/follow-up time or $\Delta BMI=(BMI_{T2}-BMI_{T1})$/follow-up time); and (4) two interaction terms; one between the average determinant and follow-up time and second between the change in the determinant and follow-up time (eg, [average TST]*time and [ΔTST]*time or [average BMI]*time and [ΔBMI]*time). To account for the correlation between measurements of the same individual, we included a random intercept in all models. We examined whether adding quadratic terms of the average measure of the independent variables improved the models. We also assessed interactions of age and sex with BMI and sleep parameters in each of the models.

In the linear mixed models, the effect estimate of the average captures how average levels of the determinant across two assessments is associated with the trajectory of the outcome across time. The effect estimate of the change captures how changes in levels of the determinant influence the trajectory of the outcome across time. The interaction terms capture changes in the observed associations with time. Analyses were conducted using SPSS software version 21.0 (IBM SPSS Statistics for Windows, Armonk, NY: IBM Corp) and R (Version 3.4.1) [37].

2.6. Sensitivity analyses

Since BMI might be an imperfect measure of adiposity in older adults [38], we repeated all analyses using WC. Furthermore, because we included information from two different devices in our study, we stratified the analyses by device at follow-up (GeneActiv or Actiwatch). For nonresponse analyses, participants included in the analyses were compared to those who refused to participate or were lost to follow up (n = 754), based on several demographic and health characteristics (ie, age, sex, depressive symptoms score, sleep parameters and BMI) using chi-squared, Mann–Whitney U tests, or independent sample t-tests.

3. Results

Characteristics of the study population are shown in Table 1. Mean age at baseline was 60.6 years (standard deviation (SD): 7.7) and 52.0% were women. Mean (SD) BMI was 27.9 (4.3) kg/m^2 at T1, and 27.6 (4.3) kg/m^2 at T2. The median time difference between the two visits was six years (range five to nine years). On average, BMI decreased with 0.31 kg/m^2, WC increased with 0.5 cm, TST increased with 0.16 h, SE increased with 0.70%, SOL decreased with 2.44 min and WASO decreased by 2.72 min. We observed no major differences between the sex and age adjusted models (see Supplementary Tables 1–3) and the models adjusted for confounders. Furthermore, we found no cross-sectional or longitudinal associations of BMI with WASO and SOL in the analyses adjusted for confounders (see Tables 2–4), and therefore focus on the results regarding SE and TST obtained from the adjusted models in the text. Results regarding WASO and SOL are presented in the tables only. Quadratic terms did not improve the models and no evidence was found of a sex or age interaction in any model.

3.1. Cross-sectional analyses

In cross-sectional analyses, 1-h longer TST was associated with approximately 0.5 kg/m^2 lower BMI at T1 and T2 (see Table 2). At T2, 1% higher SE was associated with 0.03 kg/m^2 (95% CI: −0.07, −0.01) lower BMI (Table 2). The change in the effect estimates was largest (~15%) after adding napping to the model. Other covariates did not affect the effect estimate substantially.

3.2. Longitudinal association of sleep parameters with repeatedly measured BMI

In the longitudinal analyses, we found that an average shorter sleep duration and an average lower sleep efficiency across the two time-points were associated with a higher BMI (main effect estimates for average sleep parameters in Table 3 and light grey lines in Fig. 1). In this sample, we also observed that with every hour longer average sleep duration, the yearly decrease in BMI of 0.20 kg/m^2 (Fig. 1; and effect of time in Table 3) was slower by 0.03 kg/m^2 (95% CI: 0.003,0.05). Additionally, with every 1% higher average sleep efficiency, the yearly decrease in BMI was slower by 0.002 kg/m^2 (95% CI: 0.00002, 0.005). Taken together, these results indicate that habitually longer and more efficient sleep is associated with lower BMI, but also a slower decrease in BMI across time (less steep slopes of light grey lines compared to dark grey lines in Fig. 1).

Furthermore, we evaluated the association between changes in sleep parameters and BMI. We observed that a decrease in sleep efficiency of 1% per year was associated with 0.21 (95% CI: 0.41, 0.02) kg/m^2 higher BMI across time (effect estimate for ΔSE in Table 3). Changes in TST across the follow up were not associated with BMI.

3.3. Longitudinal association of BMI with repeatedly measured sleep parameters

In longitudinal analyses with BMI as the exposure variable, 1 kg/m^2 higher average BMI was associated with a 0.02 h (95% CI: −0.03, −0.01) shorter TST (Table 4). The association between higher BMI and shorter TST become more pronounced over time ($\beta_{BMI*TIME} = -0.002$, 95% CI: −0.004, −0.00002).

When we evaluated the association between changes in BMI and sleep parameters, 1 kg/m^2 increase in BMI across the follow-up was associated with 0.23 h longer TST (95% CI: 0.04, 0.42).

Patterns of TST and SE across time for a normal weight and obese individual are visually presented in Fig. 2. Notably, for the average person in our study, a stable BMI was associated with increasing SE over time (solid lines in the right panel of Fig. 2), whereas an increase of 3 kg/m^2 BMI was associated with a decrease in SE over time (dotted lines in the right panel of Fig. 2). This decrease in SE

Table 1
Characteristics of the study population, Rotterdam study, 2004–2014.

	T1 (December 2004–April 2007)		T2 (March 2009–June 2014)	
	n (%)	Mean (SD)	n (%)	Mean (SD)
Participants	1031		1031	
Age (years)		60.6 (7.7)		66.8 (7.9)
Female sex	535 (52.0)		555 (52.0)	
BMI (kg/m^2)		27.9 (4.3)		27.6 (4.3)
WC (cm)		94.1 (12.3)		94.6 (12.2)
Total sleep time (hours)		6.0 (0.9)		6.2 (0.9)
Sleep efficiency (%)		74.8 (8.6)		75.5 (8.6)
Sleep onset latency (minutes)		20.8 (17.7)		18.3 (16.8)
Wake after sleep onset (minutes)		61.8 (58.1)		59.1 (54.7)
Education[a]				
Primary education	71 (6.9)			
Lower education	403 (39.1)			
Intermediate education	311 (30.2)			
Higher education	246 (23.9)			
Employed	385 (37.3)		284 (27.5)	
Prevalent chronic disease	289 (28.0)		383 (37.2)	
Smoking				
Non smoker	328 (31.8)		345 (33.5)	
Former smoker	538 (52.2)		564 (54.7)	
Current smoker	165 (16.0)		121 (11.7)	
Alcohol consumption (glasses/day)		1.13 (0.86)		0.88 (0.85)
Physical activity (MET hours/week)[a]		NA		64.6 (65.4)
Depressive symptoms score[b]		4.3 (6.2)		4.7 (6.6)
Self-reported frequency of sleep disordered breathing				
Not in the past month	845 (82.0)		837 (81.2)	
Less than once per week	63 (6.1)		76 (7.4)	
Once or twice per week	67 (6.5)		56 (5.4)	
More than twice per week	56 (5.4)		62 (6.0)	
Number of days with a nap	1.5 (1.9)		1.6 (1.9)	

Abbreviations: BMI, body mass index; MET, metabolic equivalent of task; NA, not applicable; T, time point; WC, waist circumference.
[a] Education was only assessed at baseline and physical activity only at follow-up.
[b] The depressive symptoms score did not include the question on restless sleep.

Table 2
Cross-sectional associations of objective sleep with body mass index (kg/m^2) at two time points, Rotterdam study, 2004–2014.

	Associations at T1 (Dec 2004–Apr 2007)		Associations at T2[a] (Mar 2009–Jun 2014)	
	B	95% CI	B	95% CI
TST, hours	−0.51	−0.81, −0.21	−0.58	−0.87, −0.29
SE, %	−0.01	−0.05, 0.02	−0.03	−0.07, −0.01
SOL[b], min	0.01	−0.01, 0.02	0.01	−0.003, 0.03
WASO, min	0.002	−0.008; 0.012	0.005	−0.005; 0.015

Abbreviations: BMI, body mass index; SE, sleep efficiency; SOL, sleep onset latency; T, time point; TST, total sleep time, WASO, wake after sleep onset; CI: Confidence Interval. Models are adjusted for sex, age, cohort, smoking, alcohol consumption, education, employment, prevalent chronic disease(s), CES-Depression score, self-reported frequency of sleep disordered breathing, and frequency of napping.
[a] Additionally adjusted for physical activity and actigraphy device (Actiwatch or GeneActiv).
[b] SOL was log-transformed for analyses.

seemed to be steeper for those shifting from overweight to obese (30 kg/m^2 to 33 kg/m^2), compared to changes within the normal weight range.

3.4. Sensitivity analyses

Results for WC were similar to those of BMI (Supplementary Table 4–6). Results were also similar across the two actigraphy devices (data not shown). The nonresponse analysis indicated that participants included in the study were more likely to be highly educated ($\chi^2 = 12.855$, $P = 0.005$), but did not differ from those lost to follow-up in terms of age, sex, depressive symptom score, sleep parameters, or baseline BMI.

4. Discussion

In this population-based cohort, we observed cross-sectional associations of short and disturbed sleep with higher BMI, as found in most previous studies. In longitudinal analyses, we found evidence for a complex bidirectional association between sleep and body size in the elderly. In our middle-aged and elderly population, actigraphic indices of poor sleep (eg, shorter sleep duration and lower sleep efficiency) were associated with higher BMI. Better sleep (ie, longer TST and greater SE) was also related to a slower decrease in BMI across time. Conversely, a higher average BMI was associated with decreased sleep duration, and this association was more pronounced with time.

Most cross-sectional studies reported that short and fragmented sleep are associated with high BMI and obesity [27,39–42], whereas a few found no association [11–14]. These differences between studies might be related to the method used to measure sleep parameters, as information obtained by self-report does not necessarily reflect objective sleep [18]. Meta-analyses, however, observed an overall cross-sectional association between sleep duration and body composition [15,16]. This finding is supported by evidence from longitudinal studies using subjective measures of

Table 3
The prospective association of sleep parameters and repeatedly measured BMI.

	BMI (kg/m^2)	
	β	95% CI
1. Total sleep time (TST), hours		
Average TST	−0.75	−1.08, −0.42
Δ TST	−1.57	−3.51, 0.36
Time, years	−0.20	−0.34, −0.07
Average TST & Time Interaction	0.03	0.003, 0.05
Δ TST & Time Interaction	−0.05	−0.18, 0.08
2. Sleep efficiency (SE), %		
Average SE	−0.04	−0.08, −0.01
Δ SE	−0.21	−0.41, −0.02
Time, years	−0.22	−0.40, −0.05
Average SE & Time Interaction	0.00	0.00, 0.01
Δ SE & Time Interaction	−0.01	−0.02, 0.005
3. Sleep onset latency (SOL), minutes		
Average SOL	0.39	−0.03, 0.81
Δ SOL	0.04	−1.85, 1.93
Time, years	−0.03	−0.12, 0.05
Average SOL & Time Interaction	−0.01	−0.03, 0.02
Δ SOL & Time Interaction	−0.02	−0.15, 0.11
4. Wake after sleep onset (WASO), minutes		
Average WASO	0.004	−0.01, 0.02
Δ WASO	0.010	−0.06, 0.08
Time, years	−0.03	−0.08, 0.02
Average WASO & Time Interaction	−0.00	−0.00, 0.00
Δ WASO & Time Interaction	0.01	0.00, 0.01

Abbreviations: BMI, body mass index; CI: Confidence Interval.
β's are derived from linear mixed models. Time is expressed as 0 = baseline and $Date_{BMI\_T2} - Date_{BMI\_T1}$ = follow-up, average BMI is expressed as $(BMI_{T2} + BMI_{T1})/2$, Δ BMI is expressed as $(BMI_{T2} - BMI_{T1})$/follow-up time.
The interaction term estimates how the effects of the average of the sleep parameter and time depend on each other.
Models are adjusted for sex, age, cohort, actigraphy device at follow-up, smoking, alcohol consumption, education, employment, prevalent chronic disease(s), depressive symptoms, self-reported frequency of sleep disordered breathing, and frequency of napping.
SOL was log-transformed in analyses.

sleep, and short sleep is therefore increasingly recognized as a potential risk factor for obesity [3,43]. Our prospective findings are in line with these observations, and show that actigraphic indices of longer and more efficient sleep are associated with a lower BMI across time. We also show that in middle-aged and older adults sufficient and efficient sleep is associated with a slower decrease in BMI. This indicates that optimal sleep parameters are associated with a healthier and more stable BMI in middle-aged and older adults. However, since participants with longer sleep duration had a lower BMI at baseline, the observed effects could be explained by the smaller probability of BMI decline among these persons. Nevertheless, a stable BMI is particularly important in this population, since weight loss, intentional or unintentional, at older age is often associated with disease [44,45]. It has been reported that the association between sleep and BMI differs with age [39]. Our observation that longer sleep duration is associated with a slower decrease in BMI may therefore be specific to middle-aged and older adults. Taken together, our results suggest that a longer sleep duration might be beneficial for health in middle-aged and older adults, as it was associated with a healthy and stable BMI in this population, both factors related to good health [46].

Alternately, other factors related to short sleep and high BMI, such as reduced physical activity or napping might also contribute to this association [47]. Indeed, napping was the variable that changed the effect estimate the most after adding it to our cross-sectional models. However, longitudinal associations were still present after correction for confounding, indicating that physical activity and napping do not fully explain the association between sleep and BMI. Further, we cannot rule out that residual confounding explains the relation between shorter sleep duration and higher BMI (eg, genetic predisposition, stress, sleep disorders etc.). Conversely, longer sleep measured with actigraphy may be a marker of long periods of inactivity (ie, awake in bed) that could be related to weight gain or slower decrease in BMI.

Many studies have focused on the association from sleep to adiposity, whereas the converse association has gained less attention. Only one previous study explored the direction of this association using subjective sleep measures [14]. The authors reported that a higher BMI predicted a small decrease in self-reported sleep duration over time, but not vice versa [14]. We demonstrated that while objectively measured short sleep is prospectively associated with a higher BMI, a high BMI is also prospectively associated with shorter objectively measured sleep duration. Notably, we showed that high BMI was associated with a reduction in sleep duration and efficiency over time. While this is in line with the observation by Garfield et al. [14], the findings that shorter sleep is prospectively associated with higher BMI in our study do not correspond to the results they obtained for the association in this direction. The inconsistencies of the prospective association from sleep to BMI could be due to the smaller changes in BMI observed in their cohort, compared to our cohort. However, the changes in self-reported sleep duration observed by Garfield et al., were smaller compared to changes observed in our study, yet the observed prospective effects from BMI to sleep were present. This could indicate that prospective effects of BMI on sleep patterns is more long term than the reverse. Based on our model, if a 61-year-old overweight (30 kg/m^2) male person became obese (33 kg/m^2), a reduction of 2.25% in sleep efficiency over nine years follow-up could be expected. In the converse association, a 10% decrease in sleep efficiency was related

Table 4
The prospective association of BMI with repeatedly measured actigraphic sleep parameters.

	Total sleep time (TST), hours		Sleep efficiency (SE), %		Sleep onset latency (SOL), minutes		Wake after sleep onset (WASO), minutes	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Average BMI (kg/m^2)	−0.02	−0.03, −0.01	−0.04	−0.17, 0.08	0.01	−0.003, 0.02	0.02	−0.36, 0.41
Δ BMI (kg/m^2)	0.23	0.04, 0.42	1.75	−0.06, 3.57	0.00	−0.15, 0.16	−3.97	−9.40, 1.46
Time (years)	0.08	0.03, 0.14	0.74	0.20, 1.29	−0.02	−0.08, 0.03	−1.14	−2.70, 0.42
Average BMI & Time Interaction	−0.00	−0.00, −0.00	−0.02	−0.04, −0.00	0.00	−0.00, 0.00	0.03	−0.03, 0.08
Δ BMI & Time Interaction	−0.01	−0.03, 0.02	−0.13	−0.42, 0.15	−0.003	−0.03, 0.03	0.69	−0.12, 1.50

Abbreviations: BMI, body mass index; CI: Confidence Interval.
β's are derived from linear mixed models. Time is expressed as 0 = baseline and $Date_{Sleep\_T2} - Date_{Sleep\_T1}$ = follow-up, average BMI is expressed as $(BMI_{T2} + BMI_{T1})/2$, Δ BMI is expressed as $(BMI_{T2} - BMI_{T1})$/follow-up time. The interaction term estimates how the effects of average BMI and time depend on each other.
Models are adjusted for sex, age, cohort, actigraphy device at follow-up, smoking, education, alcohol consumption, employment, prevalent chronic disease(s), depressive symptoms, self-reported frequency of sleep disordered breathing, and frequency of napping.
SOL was log-transformed in analyses.

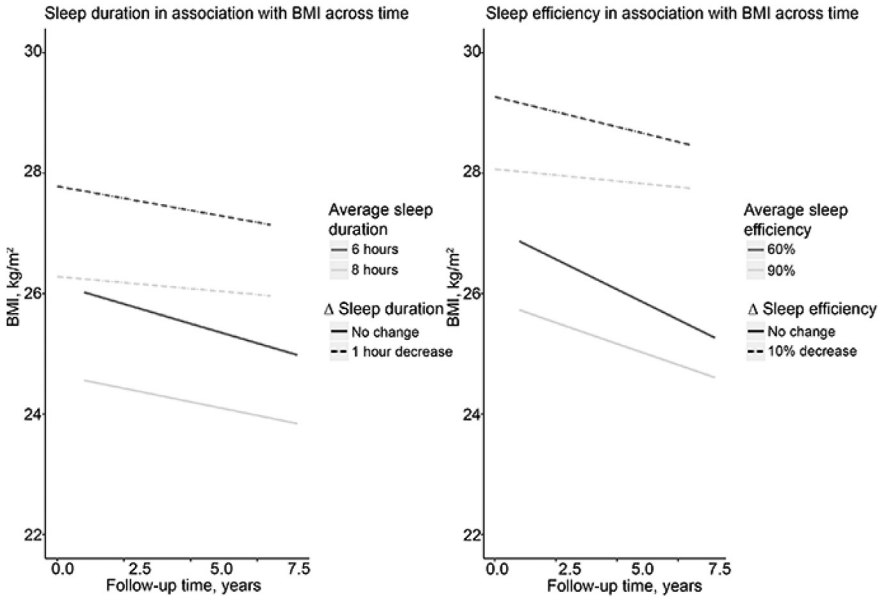

Fig. 1. Actigraphically Measured Sleep Parameters Predicting Body Mass Index Across Time, an example of a Good (Light Grey) and Poor (Dark Grey) Sleeper. TST is total sleep time in hours, SE is sleep efficiency in %. Light grey indicates "poor sleep" (eg, TST = 6 h, SE = 60%), Dark grey indicates "good sleep" (eg, TST = 8 h, SE = 90%). Dotted lines indicate worsening of sleep parameters relative to the respective color (eg, ↓1 h TST, ↓10% SE). Estimates are representative of a non-smoking, high-educated male of 61 years old, with no sleep disordered breathing or other comorbidities, and median level of alcohol consumption, physical activity and depressive symptoms.

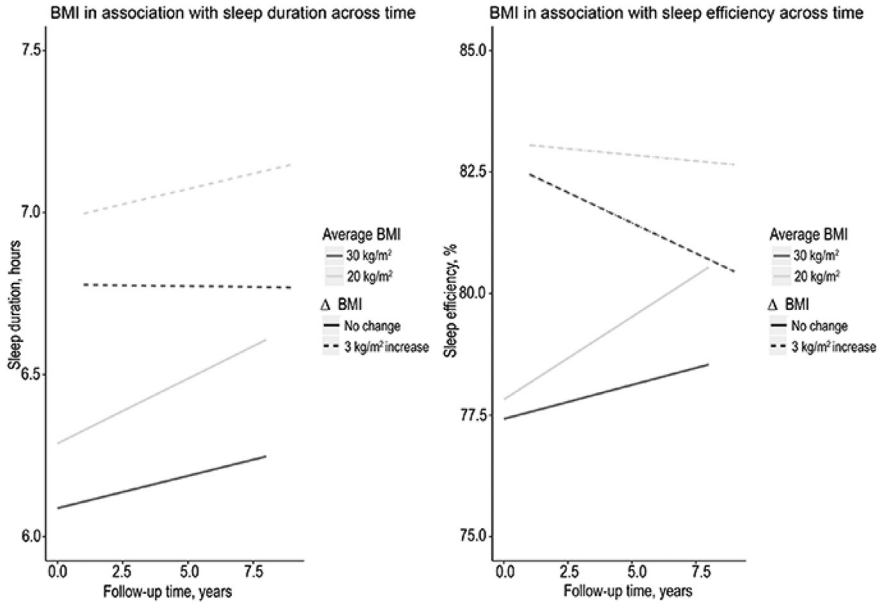

Fig. 2. Body Mass Index Predicting Actigraphically Measured Sleep Parameters Across Time, an example of Normal Weight (Dark Grey) and Obese (Light Grey) Person. TST is total sleep time in hours, SE is sleep efficiency in %. Light grey represents the estimates for a BMI of 30 kg/m^2, dark grey represents the estimates for a person BMI of 20 kg/m^2, and dotted lines indicate three points decrease from the respective color. Estimates are for a non-smoking, high-educated male of 61 years old, with no sleep disordered breathing or other comorbidities, and median level of alcohol consumption, physical activity and depressive symptoms.

to 2.2 kg/m^2 higher BMI over a follow-up of nine years. This confirms that the relation between sleep and body size is bidirectional, and changes in either sleep or BMI are likely to co-occur with changes in health through multiple pathways. Nevertheless, as noted by the small effect sizes, the clinical significance of these differences or changes is likely small.

The mechanisms underlying the association between obesity and sleep might be related to health status, as chronically ill people are more likely to experience sleep difficulties or disturbances [48]. Yet, adjustments for chronic diseases and other health-related variables did not meaningfully change our results. People with higher BMI are also more likely to snore or experience symptoms of sleep disordered breathing, which in turn can result in shorter and more fragmented sleep [49]. Almost 20% of our sample reported the experience of long breathing pauses during sleep. Some of these persons may suffer from sleep apnea, which is likely to partly explain the longitudinal associations between high BMI and short or disturbed sleep.

To the best of our knowledge, there are no other observational studies exploring how changes in objectively measured sleep

parameters are associated with BMI or how changes in body size are associated with sleep. Some intervention studies have examined the effect of weight loss on sleep [20–22,50], reporting that weight loss programs result in an increase in self-reported sleep duration [20,22]. In our study, an increase in BMI across the follow-up was related to longer sleep duration. This, again, could be related to the fact that actigraphy measures movement. People who gain weight at an older age could spend increasing time in bed while laying still, which will typically be scored as sleep. Alternatively, people who gain some weight at an older age might be healthier, and thus sleep better, compared to those who lose weight due to chronic illness.

Major strengths of our study are the prospective design with repeated measures of sleep and BMI across a follow-up of six years in a large sample of middle-aged and older adults from the general population. In contrast to the only previous longitudinal BMI study which measured sleep objectively [35], next to repeated anthropometric measures, we also had repeated measures of sleep, allowing us to accurately estimate average between-subject differences in both directions of the association. The longitudinal design of the study allowed us to explore changes over time, and to explore reverse causality, which may influence associations observed in cross-sectional studies.

We acknowledge that our study has some methodological limitations. First, we did not have an objective measure of SDB, but relied on self-report. Additionally, we only had information on the presence and not on the severity of chronic diseases. These two limitations might give rise to some degree of residual confounding. In our follow-up measurement we used two different devices to measure sleep, which might result in increased measurement error. In addition, our nonresponse analysis indicated that participants included in the study were more likely to be highly educated, and this association might differ in populations with different sociodemographic characteristics. Furthermore, BMI does not indicate how fat is distributed across the body and by evaluating changes in BMI, we did not have information on whether lean mass or fat mass was lost over time. Nevertheless, BMI has been shown to be a reasonably good measure to assess adiposity [51] and our results using WC were in line with the results obtained by BMI.

In conclusion, in this population there was a clear bidirectional association between sleep and body size across a follow-up of six years. Indices of good sleep (eg, longer sleep duration, higher sleep efficiency) were associated with a lower BMI, and were also related to a slower decline in BMI among middle-aged and older adults. Conversely, lower BMI was associated with longer sleep duration, and this association was more pronounced with time. The findings from our general population sample suggest that sleep and body size have a complex interrelationship with health in middle-aged and older adults. Longer and more efficient sleep might help these adults to maintain a healthy body weight, and a healthy BMI is associated with better sleep indices in an age group with increasing sleep problems and disturbances.

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Conflict of interest

The authors declare no competing interest.

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2019.01.034.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sleep.2019.01.034.

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