ORIGINAL RESEARCH

Association of Sleep Duration, Napping, and Sleep Patterns With Risk of Cardiovascular Diseases: A Nationwide Twin Study

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BACKGROUND: Although sleep disorders have been linked to cardiovascular diseases (CVDs), the association between sleep characteristics and CVDs remains inconclusive. We aimed to examine the association of nighttime sleep duration, daytime napping, and sleep patterns with CVDs and explore whether genetic and early-life environmental factors account for this association.

METHODS AND RESULTS: In the Swedish Twin Registry, 12,268 CVD-free twin individuals (mean age=70.3 years) at baseline were followed up to 18 years to detect incident CVDs. Sleep duration, napping, and sleep patterns (assessed by sleep duration, chronotype, insomnia, snoring, and daytime sleepiness) were self-reported at baseline. CVDs were ascertained through the Swedish National Patient Registry and the Cause of Death Register. Data were analyzed using a Cox model. In the multiadjusted Cox model, compared with 7 to 9 hours/night, the hazard ratios (HRs) of CVDs were 1.14 (95% CI, 1.01–1.28) for <7 hours/night and 1.10 (95% CI, 1.00–1.21) for ≥10 hours/night, respectively. Compared with no napping, napping 1 to 30 minutes (HR, 1.11 [95% CI, 1.03–1.18]) and >30 minutes (HR, 1.23 [95% CI, 1.14–1.33]) were related to CVDs. Furthermore, a poor sleep pattern was associated with CVDs (HR, 1.22 [95% CI, 1.05–1.41]). The co-twin matched control analyses showed similar results as the unmatched analyses, and there was no significant interaction between sleep characteristics and zygosity (P values >0.05).

CONCLUSIONS: Short or long sleep (<7 or ≥10 hours/night), napping, and poor sleep patterns are associated with an increased CVD risk. Genetic and early-life environmental factors may not account for the sleep–CVD association.

Key Words: cardiovascular diseases • cohort study • sleep • twin study

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tee, a behavior that we typically perform every day, is vitally important to our health. Sleep problems, including inappropriate or low-quality sleep, are a growing and underappreciated determinant of health. Poor sleep can, independent of primary sleep disorders, contribute to several molecular, immune, and neural changes that play a role in disease development.

Previous studies have shown that sleep duration and quality may influence the development of cardiovascular diseases (CVDs). Although insufficient sleep has been consistently reported to increase the risk of CVDs in several meta-analyses, the association of excessive sleep and CVDs requires further investigation. In addition, whether daytime napping is beneficial or
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The joint effects of nighttime sleep and daytime napping on cardiovascular diseases (CVDs) have not been well studied. Moreover, as nighttime sleep and daytime napping only reflect parts of sleep behavior, a multidimensional sleep assessment including sleep duration, chronotype, insomnia, snoring, and daytime sleepiness has been introduced to evaluate the overall sleep pattern and its impact on CVDs. However, studies undertaking this comprehensive approach to assess the impact of sleep on CVDs have been limited. Accumulating evidence showed that genetic and early-life environmental factors (such as natural environment, fetal environment, childhood socioeconomic status, etc) might influence sleep habits and cardiovascular health. However, it is unclear whether these factors could contribute to the association between sleep and CVDs. Twins who are raised together typically share their early-life environment and genetic background; therefore, a twin study design is useful to explore whether these unmeasurable factors could play a role in the sleep–CVDs association.

In the current study, we aimed to (1) examine the association of nighttime sleep duration and daytime napping with CVDs, (2) assess the overall impact of sleep on CVDs using a comprehensive sleep pattern indicator, and (3) explore whether genetic and early-life environmental factors explain the observed associations using a long-term cohort study of nationwide Swedish twins.

**METHODS**

The data that support the findings of this study are available from the corresponding author on reasonable request.

**Study Population**

The study population was drawn from the nationwide STR (Swedish Twin Registry), which began in the 1960s. During 1998 to 2002, all living twins born in 1958 or earlier were recruited to participate in the SALT (Screening Across the Lifespan Twin) study conducted by computer-assisted telephone interview. Of all participants, 14,388 twin individuals participated in the sleep survey in SALT. Of them, we excluded 120 individuals with missing information on nighttime sleep duration and/or daytime napping and 2000 individuals who had prevalent major CVDs (including coronary heart disease [CHD] and stroke) at baseline. Finally, 12,268 individuals remained and were followed up until December 31, 2016.

**Data Collection**

Information on age, sex, education, marital status (married/cohabiting, single including divorced and living alone), zygosity status (monozygotic, dizygotic, undetermined zygosity), height, weight, smoking status (never, former/current), alcohol consumption (no/mild drinking, heavy drinking), and physical activity was collected in the SALT study. Education (<8 versus ≥8 years) was defined using the years of formal schooling. Body mass index, calculated as weight (kilograms) divided by height (meter squared), was categorized into the following 4 groups: underweight (<20 kg/m²), healthy (20–24.9 kg/m²), overweight (25–29.9 kg/m²), and obese (≥30 kg/m²). The level of physical activity was dichotomized as low (including almost never and much less than average) and regular (including less than average, average, more than average, much more than average, and maximum) based on the annual exercise pattern.

Information on the medical history of type 2 diabetes, hypertension, depression, and CVDs were ascertained from the Swedish NPR (National Patient Registry), which covers all inpatient diagnoses in Sweden from...
the 1960s and outpatient care (specialist clinic) since 2001.26 Disease diagnoses were identified based on the International Classification of Diseases (ICD). The International Classification of Diseases, Seventh Revision (ICD-7) was used until 1968, the International Classification of Diseases, Eighth Revision (ICD-8) from 1969 to 1986, the International Classification of Diseases, Ninth Revision (ICD-9) from 1987 to 1996, and the International Classification of Diseases, Tenth Revision (ICD-10) since 1997.

All participants provided informed consent, and the study was approved by the Regional Ethics Board at Karolinska Institutet, Stockholm, Sweden, and the Institutional Review Board at the University of Southern California.

Assessment of Sleep Characteristics
Sleep was assessed at baseline based on the Karolinska Sleep Questionnaire, including nighttime sleep duration, daytime napping, chronotype, insomnia, snoring, and daytime sleepiness (Table S1).27 Nighttime sleep duration was divided into 4 groups: <7, 7 to 9 (ie, ≥7 to <9), 9 to 10 (ie, ≥9 to <10), or ≥10 hours/night.1,28 Daytime napping was categorized into no napping (0 minutes), 1 to 30 minutes, or >30 minutes/day. Total daily sleep duration was calculated as the sum of nighttime sleep duration and daytime napping duration.

A subsample of SALT participants (n=5464; 44.5%) had complete sleep information. Among these participants, we calculated composite sleep scores, which integrated 5 sleep characteristics (total daily sleep duration, chronotype, insomnia, snoring, and daytime sleepiness) to assess sleep patterns.17 Low-risk sleep characteristics were defined as follows: total daily sleep duration of 7 to 9 hours, morning person (definitely/to some degree a morning person), never/seldom insomnia symptoms, never heavy snoring, or never/seldom daytime sleepiness. For each sleep characteristic, a score of 1 was assigned if defined as low risk, otherwise a score of 0. Thus, the sum of the aforementioned 5 sleep characteristic scores ranged from 0 to 5. We further categorized the sleep patterns as “healthy” (≥4 scores), “intermediate” (2–3 scores), and “poor” (≤1 score).17

Assessment of CVDs
The primary outcomes of this study were major CVDs (including CHD and stroke) according to the previous studies.17 Diagnoses of CVDs were derived from the NPR and the Swedish Cause of Death Register (recording death dates and underlying and contributing death causes since 1952). CVDs were ascertained according to ICD-7 through ICD-10 codes: ICD-7 codes 420 for CHD and codes 330–332 for stroke, ICD-8/ICD-9 codes 410–414 for CHD and codes 430–434 for stroke, and ICD-10 codes I20–I25 for CHD and codes I60–I66 for stroke. The date of CVD onset was recorded according to the earliest documented date of the CVD diagnosis in the NPR or the Swedish Cause of Death Register.

Statistical Analysis
Baseline characteristics of the study participants by nighttime sleep duration were compared using $\chi^2$ tests.
for categorical variables and ANOVA for continuous variables.

The hazard ratios (HRs) and 95% CIs for the associations between sleep characteristics and CVDs were estimated using Cox proportional hazard models in unmatched analysis among all individuals. Follow-up time was calculated from the baseline date until the date of incident CVDs, date of death, or the censoring date (December 31, 2016), whichever occurred first. The analyses were clustered on twin pairs to compute a robust variance that could control for twin dependency within pairs.27 The proportional hazard assumption was assessed using the Schoenfeld residuals method, and no violation was observed. In the basic Cox model, we adjusted for age, sex, and education. In the multivariable Cox model, we additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes, hypertension, and depression.

We also used restricted cubic splines with 4 knots at the 5th, 35th, 65th, and 95th percentiles29 to visualize the association of nighttime sleep duration with CVDs. In addition, to assess the joint effects of nighttime sleep duration and daytime napping on the risk of CVDs, we created dummy variables of 12 categories according to the cross-tabulation of nighttime sleep duration (<7, 7–9, 9–10, or ≥10 hours/night) and daytime napping (0, 1–30, or >30 minutes). Multiplicative interaction between nighttime sleep duration and daytime napping was examined by adding an interaction term to the model.30

Stratified Cox models by twin pairs were used in the co-twin matched control analyses to explore the role of familial background (ie, genetic and early-life environmental factors) in the association between sleep characteristics and CVDs. Twin pairs discordant both for sleep characteristics and for CVDs status (or CVDs onset dates) were included in these analyses. Finally, 911, 847, and 323 twin pairs were included in the co-twin matched control analyses regarding nighttime sleep duration, daytime napping, and sleep patterns, respectively (Figure 1). If the associations observed in the unmatched analyses among all twin individuals were attenuated in the co-twin matched control analyses, this suggests that genetic and early-life environmental factors might contribute to this association. In addition, the multiplicative interaction term between sleep characteristics and zygosity was included in the Cox model to further examine whether genetic background might account for the sleep–CVD associations.21,24,31

Missing values on education (n=52), marital status (n=3), body mass index (n=518), smoking status (n=25), alcohol consumption (n=60), and physical activity (n=4168) were imputed using “multivariate imputation by chained equations” under the missing at random assumption.32

In the sensitivity analysis, we performed the following analyses: (1) assessing the associations between sleep characteristics and different CVDs subtypes, including CHD, angina pectoris, myocardial infarction, stroke, hemorrhagic stroke, and ischemic stroke; (2) adjusting for daytime napping when analyzing the association of nighttime sleep duration with CVDs and vice versa; (3) adjusting for anxiety; (4) excluding participants who developed CVDs (n=571) in the first 2 years of follow-up; (5) excluding participants who developed atrial fibrillation (n=351) or heart failure (n=188) before baseline; (6) excluding participants with any missing values; and (7) using the Fine-Gray subdistribution hazard model to evaluate the association between sleep characteristics and CVDs in the presence of competing events (considering noncardiovascular death as a competitive risk factor).

Statistical analyses were performed using R software version 4.0.5 (R Foundation, Vienna, Austria). The R packages were used to impute the missing data (mice, version 3.13.0), to draw restricted cubic splines (rms, version 6.2–0), and to fit Cox proportional hazards models (survival, version 3.2–10). All P values were 2-sided, and P<0.05 was considered statistically significant.

RESULTS
Characteristics of the Study Population
Of the 12 268 participants, 7036 (57.4%) were female participants, and the mean (SD) age at baseline was 70.3 (7.6) years. The mean (SD) nighttime sleep duration in the population was 8.5 (1.2) hours/night. Among all participants, 830 (6.8%), 6410 (52.2%), 3608 (29.4%), and 1420 (11.6%) had <7, 7 to 9, 9 to 10, and ≥10 hours of sleep/night at baseline, respectively. In total, 5082 (41.4%) had daytime napping, including 2897 (23.6%) with ≤30 minutes and 2185 (17.8%) with >30 minutes.

Compared with those with 7 to 9 hours of sleep/night, individuals with <7 hours of sleep/night were younger; more educated; more likely to be male sex, smokers, and heavy drinkers; and had a higher body mass index. Those with ≥10 hours of sleep/night were older, less educated, and more likely to be female sex and to have type 2 diabetes. In addition, participants with <7 or ≥10 hours of sleep/night were more likely to be single; have a low level of physical activity; and have depression, habitual daytime napping, and poor sleep patterns (Table 1). Baseline characteristics of the study population by sleep pattern are shown in Table S2.

Association Between Sleep Characteristics and CVDs
During a median follow-up of 12.9 years, 4779 participants developed CVDs, including 3251 CHD and 2292 stroke cases. Restricted cubic spline demonstrated a
U-shaped curve for the association between nighttime sleep duration and CVDs, with the indication that people with 7 to 9 hours of nighttime sleep had the lowest risk of CVDs (Figure 2). Therefore, 7 to 9 hours of sleep/night was used as the reference group in the analyses. In multivariable-adjusted Cox models, compared with 7 to 9 hours of sleep/night, <7 (HR, 1.14 [95% CI, 1.01–1.28]) and ≥10 (HR, 1.10 [95% CI, 1.00–1.21]) hours of sleep/night were associated with an increased risk of CVDs. Compared with no napping, 1 to 30 minutes...
Short and long nighttime sleep (<7 or ≥10 hours/night) and daytime napping were associated with a moderately increased risk of CVDs. Furthermore, compared with the healthy sleep pattern, the poor sleep pattern comprised negative sleep characteristics (ie, insufficient/excessive sleep, evening chronotype, frequent insomnia, heavy snoring, frequent daytime sleepiness) was associated with CVDs, and genetic and early-life environmental factors might not account for the sleep–CVD association.

Supplementary Analysis

Similar results were obtained when we repeated the following analyses: (1) analyzing the association of sleep characteristics with CHD, angina pectoris, myocardial infarction, stroke, hemorrhagic stroke, and ischemic stroke separately (Table S4); (2) adjusting for nighttime sleep duration and daytime napping mutually (Table S5); (3) adjusting for anxiety (Table S6); (4) excluding participants who developed CVDs within the first 2 years of follow-up (Table S7); (5) excluding participants who developed atrial fibrillation or heart failure before baseline (Table S8); (6) excluding participants with any missing values (Table S9); and (7) performing competing risk analysis (Table S10).

DISCUSSION

In this large-scale prospective cohort study of nationwide Swedish twins, we found the following: (1) both short and long nighttime sleep (<7 or ≥10 hours/night) and daytime napping were associated with a moderately increased risk of CVDs, (2) poor sleep patterns comprising negative sleep characteristics (ie, insufficient/excessive sleep, evening chronotype, frequent insomnia, heavy snoring, frequent daytime sleepiness) was associated with CVDs, and (3) genetic and early-life environmental factors might not account for the sleep–CVD association.

In line with previous studies, we observed a U-shaped association between nighttime sleep duration and CVDs, indicating that both short and long nighttime sleep were detrimental to cardiovascular health.4–6,33 However, the definitions of short (such as <5, <6, or <7 hours)5 and long sleep (such as >8, >9, or >10 hours)33 have been variable in previous studies. A Joint Consensus Statement has recommended that the optimal nighttime sleep duration for adults is 7 to 9 hours, and sleeping <7 hours/night is considered to be associated with adverse health outcomes.28 In line with this definition, our study found that nighttime sleep of <7 hours was detrimental to cardiovascular health.28 Similar to several previous studies, we observed that sleeping ≥10 hours/night was also related to a higher risk of CVDs.33,34
Although daytime napping is perceived as a common behavior in older adults, its long-term effect on cardiovascular health remains unclear. A meta-analysis showed that daytime napping of ≥60 minutes was associated with an increased risk of CVDs. In contrast, a Swiss cohort study found that napping once or twice a week was protective against CVDs. In the present study, compared with no napping, both napping 1 to 30 and >30 minutes were associated with an increased risk of CVDs.

The importance of taking into account daytime napping in understanding the association of nighttime sleep duration with cardiovascular risk has been addressed, but few studies have been able to study the interplay between daytime napping and nighttime sleep on CVDs. One study found that daytime napping was associated with increased CVDs in those who slept >6 hours/night, but not in those who slept ≤6 hours/night. Another study showed joint effects of sleeping ≥9 hours/night and midday napping >90 minutes on stroke. In the current study, the highest risk of CVDs was shown in individuals with <7 hours of sleep/night and napping ≥30 minutes, and daytime napping was still related to a higher risk of CVDs, even in those with adequate nighttime sleep (7 to 9 hours/night). However, we did not detect a statistically significant interaction in our study.

In addition to nighttime sleep and daytime napping, chronotype, insomnia, snoring, and daytime sleepiness also contribute to the overall sleep pattern. Individuals with later chronotype were more prone to sleep complaints such as insufficient sleep and insomnia. Previous studies found that short sleep with insomnia or poor sleep quality and snoring with daytime sleepiness were associated with a higher risk of CVDs. Snoring could indicate sleep-disordered breathing, which might cause acute or long-term adverse effects on heart health. Therefore, it is plausible that different sleep characteristics may influence each other and jointly affect cardiovascular health. By applying a comprehensive assessment of sleep incorporating these characteristics, in line with 2 previous studies, we might be able to better understand the complex relationship between sleep and cardiovascular health.

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**Figure 3. Sleep characteristics and risks of cardiovascular diseases.**
Forest plot illustrating the estimated hazard ratios (HRs) and 95% CIs of cardiovascular diseases in relation to sleep characteristics. Adjusted for age, sex, education, marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes, hypertension, and depression. *P<0.05.

| Sleep characteristics | Cases/Person-Years | HR(95%CI) |
|----------------------|--------------------|-----------|
| **Sleep duration**    |                    |           |
| <7 hours/night       | 322/10 245         | 1.14 (1.01−1.28) |
| 7 to 9 hours/night   | 2397/79 772        | Reference |
| 9 to 10 hours/night  | 1470/41 784        | 1.03 (0.96−1.10) |
| ≥10 hours/night      | 590/14 051         | 1.10 (1.00−1.21)* |
| **Daytime napping**  |                    |           |
| 0 minutes            | 2553/90 568        | Reference |
| 1−30 minutes         | 1226/33 624        | 1.11 (1.03−1.18) |
| >30 minutes          | 1000/21 661        | 1.23 (1.14−1.33) |
| **Sleep pattern**    |                    |           |
| Healthy              | 636/23 257         | Reference |
| Intermediate         | 1149/37 503        | 1.06 (0.96−1.17) |
| Poor                 | 280/7574           | 1.22 (1.05−1.41) |
activity, disrupt circadian rhythms, which in turn can accelerate the occurrence of cardiovascular risk factors such as diabetes, obesity, atherosclerosis, and hypertension. Prolonged sleep, however, may be a marker that requires medical, neurological, or psychiatric evaluations, especially for older adults. These subclinical states manifested by long sleep may be the underlying cause of CVDs. In addition, after daytime napping, the activation of the sympathetic nervous system can lead to a rapid rise in blood pressure and heart rate. A prolonged nap can enter deep slow-wave sleep but often fail to complete the normal sleep cycle, thereby disrupting circadian rhythms.

The strengths of our study include the large sample of nationwide twins, the long-term follow-up period, and the comprehensive assessment of sleep. The twin cohort provides us a unique opportunity to explore the role of genetic and early-life environmental factors in the sleep–CVD association. However, several limitations need to be acknowledged. First, all sleep characteristics were self-reported, which may lead to potential misclassification. However, the misclassification is likely to be nondifferential, thus leading to an underestimation of the observed associations. Although objective sleep measures, such as actigraphy or polysomnography, can provide more accurate sleep assessments, self-reported sleep measures may be used as an easy tool to target individuals at risk of health outcomes. Second, sleep was evaluated only at baseline; therefore, the potential fluctuation of sleep during follow-up was not taken into account. Third, although we included multiple potential confounders in our analyses, residual confounding (such as air pollution and rural–urban environments) could not be taken into account in the analysis because such data were unavailable. Finally, the present study was conducted on twin individuals in Sweden where relatively the winter time is longer and daytime is shorter than in other countries. Thus, caution is required when generalizing our findings to the general population in other countries.

### CONCLUSIONS

In conclusion, our study provides evidence that insufficient (<7 hours/night) or excessive (≥10 hours/night) nighttime sleep, daytime napping, and a poor sleep pattern are associated with an increased risk of CVDs. Genetic and early-life environmental factors may not account for the observed associations. Our findings encourage the adoption of an appropriate night sleep duration (7–9 hours/night) and a healthy sleep pattern to prevent the development of CVDs.

### ARTICLE INFORMATION

Received March 3, 2022; accepted May 24, 2022.

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### Table 2. HRs and 95% CIs for the Association Between Sleep Characteristics and Cardiovascular Diseases Among Co-Twin Matched Pairs: Results From Stratified Cox Models

| Sleep characteristics | No. of pairs | HR (95% CI)* | HR (95% CI)† |
|------------------------|--------------|--------------|--------------|
| Sleep duration, h/night|              |              |              |
| <7                     | 911          | 1.11 (0.79–1.55) | 1.03 (0.72–1.46) |
| 7–9                    | Reference    | Reference    |              |
| 9–10                   | 1.02 (0.85–1.22) | 1.01 (0.83–1.21) |              |
| ≥10                    | 1.10 (0.83–1.47) | 1.09 (0.81–1.47) |              |
| Daytime napping, min   | 847          |              |              |
| 0                      | Reference    | Reference    |              |
| 1–30                   | 1.28 (1.06–1.55) | 1.22 (1.00–1.49)† |              |
| >30                    | 1.50 (1.19–1.90) | 1.44 (1.13–1.85) |              |
| Sleep pattern          | 323          |              |              |
| Healthy                | Reference    | Reference    |              |
| Intermediate           | 1.83 (1.14–2.05) | 1.61 (1.17–2.23) |              |
| Poor                   | 1.79 (1.17–2.74) | 1.73 (1.10–2.74) |              |

HR indicates hazard ratio.
*Adjusted for sex and education.
†Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes, hypertension, and depression.
‡P<0.05.

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In conclusion, our study provides evidence that insufficient (<7 hours/night) or excessive (≥10 hours/night) nighttime sleep, daytime napping, and a poor sleep pattern are associated with an increased risk of CVDs. Genetic and early-life environmental factors may not account for the observed associations. Our findings encourage the adoption of an appropriate night sleep duration (7–9 hours/night) and a healthy sleep pattern to prevent the development of CVDs.
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Supplemental Material
Table S1. Sleep characteristic information questionnaire.

| Sleep characteristics     | Questionnaire                                                                 | Response options                             |
|----------------------------|------------------------------------------------------------------------------|----------------------------------------------|
| Nighttime sleep duration*  | What time do you usually go to bed and get up?                               | Get up at [time]                               |
|                            |                                                                              | Go to bed at [time]                           |
| Daytime napping            | Do you usually take a nap at least every second day? If yes, how long do you nap? | Yes [minutes]                                 |
|                            |                                                                              | No                                           |
| Chronotype                 | Try to determine to what degree you are a ‘morning person’ or a ‘night person’. | Definitely a morning person                   |
|                            |                                                                              | To some degree a morning person               |
|                            |                                                                              | To some degree a night person                 |
|                            |                                                                              | Definitely a night person                     |
| Insomnia                   | Have you experienced difficulty falling asleep or continuously waking up and difficulty falling asleep again? | Never                                        |
|                            |                                                                              | Seldom                                        |
|                            |                                                                              | Sometimes                                     |
|                            |                                                                              | Usually                                       |
|                            |                                                                              | Always                                        |
| Snoring                    | Have you experienced heavy snoring?                                         | Never                                        |
|                            |                                                                              | Seldom                                        |
|                            |                                                                              | Sometimes                                     |
|                            |                                                                              | Usually                                       |
|                            |                                                                              | Always                                        |
| Daytime sleepiness         | Have you experienced sleepiness during day time?                            | Never                                        |
|                            |                                                                              | Seldom                                        |
|                            |                                                                              | Sometimes                                     |
|                            |                                                                              | Usually                                       |
|                            |                                                                              | Always                                        |

* Nighttime sleep duration was defined as the time difference between “Go to bed” and “Get up”.
### Table S2. Baseline characteristics of the study population by sleep pattern (N = 5464).

| Characteristics            | Healthy (n = 1784) | Intermediate (n = 3023) | Poor (n = 657) | P value |
|----------------------------|--------------------|-------------------------|----------------|---------|
| Age (years)                | 67.5±8.3           | 69.0±8.4                | 69.7±8.5       | <0.001  |
| Female                     | 882 (49.4)         | 1721 (56.9)             | 387 (58.9)     | <0.001  |
| Education *                |                    |                         |                |         |
| <8 years                   | 914 (51.3)         | 1619 (53.8)             | 375 (57.2)     | 0.029   |
| ≥8 years                   | 867 (48.7)         | 1389 (46.2)             | 281 (42.8)     |         |
| Marital status             |                    |                         |                |         |
| Married/cohabiting         | 1257 (70.5)        | 2077 (68.8)             | 445 (67.7)     | 0.321   |
| Single                     | 527 (29.5)         | 944 (31.2)              | 212 (32.3)     |         |
| Zygosity                   |                    |                         |                |         |
| Monozygotic                | 328 (18.4)         | 554 (18.3)              | 132 (20.1)     | 0.253   |
| Dizygotic                  | 1260 (70.6)        | 2176 (72.0)             | 471 (71.7)     |         |
| Undetermined zygosity      | 196 (11.0)         | 293 (9.7)               | 54 (8.2)       |         |
| Body mass index (kg/m²) *  | 24.8±3.4           | 25.1±3.5                | 25.5±3.9       | <0.001  |
| <20 (Underweight)         | 84 (4.9)           | 160 (5.5)               | 22 (3.5)       | 0.001   |
| 20–24.9 (Normal weight)   | 898 (51.9)         | 1377 (47.1)             | 286 (45.0)     |         |
| 25–29.9 (Overweight)       | 637 (36.8)         | 1147 (39.2)             | 265 (41.7)     |         |
| ≥30 (Obese)               | 112 (6.5)          | 242 (8.3)               | 62 (9.8)       |         |
| Smoking status *           |                    |                         |                |         |
| Never                     | 1049 (58.9)        | 1756 (58.2)             | 363 (55.3)     | 0.285   |
| Former/current smoking    | 733 (41.1)         | 1260 (41.8)             | 293 (44.7)     |         |
| Alcohol consumption *      |                    |                         |                |         |
| No/mild drinking          | 1715 (96.3)        | 2854 (94.9)             | 614 (94.3)     | 0.031   |
| Heavy drinking            | 65 (3.7)           | 154 (5.1)               | 37 (5.7)       |         |
| Physical activity *        |                    |                         |                |         |
| Regular                   | 1017 (80.9)        | 1506 (77.1)             | 262 (67.7)     | <0.001  |
| Low                       | 240 (19.1)         | 448 (22.9)              | 125 (32.3)     |         |
| Type 2 diabetes mellitus   | 90 (5.0)           | 217 (7.2)               | 55 (8.4)       | 0.003   |
| Hypertension               | 664 (37.2)         | 1190 (39.4)             | 272 (41.4)     | 0.127   |
| Depression                | 30 (1.7)           | 67 (2.2)                | 24 (3.7)       | 0.013   |

Data are presented as mean ± standard deviation or number (proportion, %).
* Missing data: 19 for education, 173 for body mass index, 10 for smoking status, 25 for alcohol consumption, and 1866 for physical activity.
Table S3. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular diseases in relation to sleep characteristics; results from Cox models.

| Sleep characteristics | Cases/ Person-Years | HR (95% CI) * | HR (95% CI) † |
|-----------------------|---------------------|---------------|---------------|
| **Sleep duration** (hours/night) | | | |
| <7                   | 322/10 245         | 1.18 (1.05–1.32) | 1.14 (1.01–1.28) |
| 7 to 9               | 2397/79 772        | Reference      | Reference     |
| 9 to 10              | 1470/41 784        | 1.02 (0.96–1.09) | 1.03 (0.96–1.10) |
| ≥10                  | 590/14 051         | 1.10 (1.00–1.21) | 1.10 (1.00–1.21) |
| **Daytime napping** (minutes) | | | |
| 0                    | 2553/90 568        | Reference      | Reference     |
| 1–30                 | 1226/33 624        | 1.14 (1.06–1.22) | 1.11 (1.03–1.18) |
| >30                  | 1000/21 661        | 1.30 (1.20–1.40) | 1.23 (1.14–1.33) |
| **Sleep pattern** ‡ | | | |
| Healthy              | 636/23 257         | Reference      | Reference     |
| Intermediate         | 1149/37 503        | 1.09 (0.99–1.20) | 1.06 (0.96–1.17) |
| Poor                 | 280/7574           | 1.27 (1.09–1.47) | 1.22 (1.05–1.41) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=5464).
§ P <0.05.
Table S4. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular disease subtypes in relation to sleep characteristics; results from Cox models.

| Sleep characteristics          | Coronary heart diseases | Stroke                        |
|--------------------------------|-------------------------|-------------------------------|
|                                | Cases/Person-Years      | HR (95% CI) *                 | Cases/Person-Years | HR (95% CI) * |
| Sleep duration (hours/night)   |                         |                               |                  |              |
| <7                             | 228/10 767              | 1.21 (1.05–1.39)              | 152/11 399       | 1.17 (0.99–1.38) |
| 7 to 9                         | 1618/83 695             | Reference                      | 1166/87 373     | Reference     |
| 9 to 10                        | 1013/43 972             | 1.06 (0.98–1.15)              | 678/45 933      | 0.94 (0.86–1.04) |
| ≥10                            | 392/14 988              | 1.11 (0.99–1.24)              | 296/15 292      | 1.11 (0.97–1.27) |
| Daytime napping (minutes)      |                         |                               |                  |              |
| 0                              | 1715/94 894             | Reference                      | 1228/98 312     | Reference     |
| 1–30                           | 857/35 432              | 1.17 (1.08–1.28)              | 572/37 329      | 1.09 (0.99–1.20) |
| >30                            | 679/23 096              | 1.29 (1.18–1.42)              | 492/24 356      | 1.29 (1.15–1.43) |
| Sleep pattern ‡                |                         |                               |                  |              |
| Healthy                        | 432/24 206              | Reference                      | 318/24 981      | Reference     |
| Intermediate                   | 787/39 478              | 1.09 (0.96–1.22)              | 555/41 080      | 1.00 (0.87–1.15) |
| Poor                           | 196/7968                | 1.31 (1.10–1.56)              | 126/8492        | 1.05 (0.85–1.30) |
| Angina pectoris                |                         |                                |                  |              |
| Myocardial infarction          |                         |                                |                  |              |
| Sleep duration (hours/night)   |                         |                                |                  |              |
| <7                             | 116/11 147              | 1.14 (0.94–1.38)              | 136/11 476      | 1.26 (1.05–1.52) |
| 7 to 9                         | 826/86 619              | Reference                      | 926/88 311      | Reference     |
| 9 to 10                        | 484/45 496              | 1.06 (0.94–1.19)              | 584/46 643      | 1.05 (0.94–1.16) |
| ≥10                            | 155/15 579              | 0.95 (0.79–1.13)              | 234/15 704      | 1.15 (0.99–1.33) |

* p < 0.05; † p < 0.01
| Sleep characteristics | Angina pectoris | | | Myocardial infarction | | | |
|-----------------------|---------------|----------------|----------------|---------------------|----------------|----------------|
|                       | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † |
| **Daytime napping** (minutes) | | | | | | |
| 0                     | 818/97 901 | Reference | Reference | 980/99 744 | Reference | Reference |
| 1–30                  | 439/36 756 | 1.28 (1.14-1.44) | 1.23 (1.10-1.39) | 511/37 661 | 1.19 (1.06-1.32) | 1.15 (1.03-1.28) |
| >30                   | 324/24 183 | 1.37 (1.20-1.56) | 1.30 (1.14-1.49) | 389/24 728 | 1.23 (1.09-1.39) | 1.16 (1.03-1.31) |
| **Sleep pattern** ‡ | | | | | | |
| Healthy               | 211/24 891 | Reference | Reference | 247/25 335 | Reference | Reference |
| Intermediate          | 387/40 777 | 1.11 (0.94-1.31) | 1.09 (0.92-1.29) | 437/41 881 | 1.04 (0.89-1.21) | 1.01 (0.86-1.18) |
| Poor                  | 104/8287 | 1.44 (1.14-1.83) | 1.39 (1.09-1.77) | 121/8 482 | 1.38 (1.11-1.72) | 1.30 (1.04-1.63) |
| **Sleep duration** (hours/night) | | | | | | |
| <7                    | 45/11 961 | 1.59 (1.15-2.20) | 1.53 (1.10-2.13) | 109/11 543 | 1.06 (0.87-1.29) | 1.04 (0.85-1.26) |
| 7 to 9                | 240/91 790 | Reference | Reference | 909/88 147 | Reference | Reference |
| 9 to 10               | 114/48 467 | 0.82 (0.65-1.02) | 0.83 (0.66-1.04) | 542/46 374 | 0.97 (0.87-1.08) | 0.98 (0.88-1.09) |
| ≥10                   | 54/16 317 | 1.11 (0.82-1.50) | 1.10 (0.81-1.50) | 228/15 475 | 1.11 (0.95-1.29) | 1.11 (0.96-1.30) |
| **Daytime napping** (minutes) | | | | | | |
| 0                     | 260/103 075 | Reference | Reference | 941/99 231 | Reference | Reference |
| 1–30                  | 105/39 465 | 0.93 (0.73-1.17) | 0.90 (0.72-1.14) | 454/37 671 | 1.13 (1.01-1.27) | 1.11 (0.99-1.24) |
| >30                   | 88/25 995 | 1.12 (0.87-1.44) | 1.08 (0.84-1.38) | 393/24 637 | 1.35 (1.19-1.52) | 1.29 (1.14-1.46) |

**Note:** HR = hazard ratio, 95% CI = 95% confidence interval.
| Sleep characteristics | Hemorrhagic stroke | Ischemic stroke |
|-----------------------|-------------------|-----------------|
|                       | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † |
| Healthy               | 66/26 089          | Reference       | Reference       | 247/25 214         | Reference       | Reference       |
| Intermediate          | 99/43 337          | 0.88 (0.65-1.20) | 0.86 (0.63-1.17) | 444/41 480         | 1.03 (0.88-1.20) | 1.01 (0.87-1.19) |
| Poor                  | 25/8964            | 1.06 (0.67-1.67) | 1.01 (0.64-1.61) | 95/8557            | 1.03 (0.81-1.31) | 0.99 (0.78-1.26) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=5,464).
Table S5. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular disease in relation to nighttime sleep duration and daytime napping; results from Cox models.

| Sleep characteristics | Cases/Person-Years | HR (95% CI) * |
|-----------------------|--------------------|---------------|
| **Sleep duration**    |                    |               |
| <7                    | 322/10 245         | 1.14 (1.01–1.28) |
| 7 to 9                | 2397/79 772        | Reference     |
| 9 to 10               | 1470/41 784        | 1.03 (0.96–1.10) |
| ≥10                   | 590/14 051         | 1.09 (0.99–1.20) |
| **Daytime napping**   |                    |               |
| 0                     | 2553/90 568        | Reference     |
| 1–30                  | 1226/33 624        | 1.11 (1.03–1.18) |
| >30                   | 1000/21 661        | 1.23 (1.14–1.33) |

* Adjusted for age, sex, education, marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, depression, nighttime sleep duration, and daytime napping, if applicable.
Table S6. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular diseases in relation to sleep characteristics by additionally adjusting for anxiety; results from Cox models.

| Sleep characteristics | Cases/Person-Years | HR (95% CI) * |
|-----------------------|--------------------|--------------|
| **Sleep duration** (hours/night) | | |
| <7                    | 322/10 245         | 1.14 (1.01–1.28) |
| 7 to 9                | 2397/79 772        | Reference    |
| 9 to 10               | 1470/41 784        | 1.03 (0.96–1.10) |
| ≥10                   | 590/14 051         | 1.10 (1.00–1.21)‡ |
| **Daytime napping** (minutes) | | |
| 0                     | 2553/90 568        | Reference    |
| 1–30                  | 1226/33 624        | 1.11 (1.03–1.19) |
| >30                   | 1000/21 661        | 1.23 (1.14–1.33) |
| **Sleep pattern †**  | | |
| Healthy               | 636/23 257         | Reference    |
| Intermediate          | 1149/37 503        | 1.06 (0.96–1.17) |
| Poor                  | 280/7574           | 1.22 (1.05–1.41) |

* Adjusted for age, sex, education, marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, depression, and anxiety.
† Sleep patterns were analyzed in a subsample (n=5464).
‡ P <0.05.
Table S7. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular disease in relation to sleep characteristics by excluding participants with CVDs in the first two years of follow-up (N=11 697); results from Cox models.

| Sleep characteristics | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † |
|-----------------------|-------------------|---------------|---------------|
| **Sleep duration** (hours/night) |                   |               |               |
| <7                    | 286/10 204        | 1.18 (1.04–1.34) | 1.15 (1.01–1.30) |
| 7 to 9                | 2135/79 498       | Reference     | Reference     |
| 9 to 10               | 1301/41 605       | 1.02 (0.95–1.10) | 1.03 (0.96–1.11) |
| ≥10                   | 486/13 942        | 1.06 (0.96–1.18) | 1.06 (0.96–1.17) |
| **Daytime napping** (minutes) |                   |               |               |
| 0                     | 2288/90 285       | Reference     | Reference     |
| 1–30                  | 1090/33 488       | 1.14 (1.06–1.23) | 1.11 (1.03–1.19) |
| >30                   | 830/21 477        | 1.25 (1.15–1.35) | 1.18 (1.09–1.29) |
| **Sleep pattern** ‡  |                   |               |               |
| Healthy sleep         | 570/23 189        | Reference     | Reference     |
| Intermediate sleep    | 1026/37 367       | 1.09 (0.98–1.21) | 1.07 (0.97–1.19) |
| Poor sleep            | 247/7537          | 1.27 (1.09–1.48) | 1.23 (1.05–1.43) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=5242).
Table S8. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular disease in relation to sleep characteristics by excluding participants with atrial fibrillation and heart failure before baseline (N=11 817); results from Cox models.

| Sleep characteristics       | Cases/Person-Years | HR (95% CI) * | HR (95% CI) † |
|-----------------------------|--------------------|---------------|---------------|
| **Sleep duration** (hours/night) |                    |               |               |
| <7                          | 307/10 089         | 1.16 (1.03-1.31) | 1.13 (1.00-1.27) |
| 7 to 9                      | 2301/78 207        | Reference     | Reference     |
| 9 to 10                     | 1402/40 787        | 1.03 (0.96-1.10) | 1.03 (0.97-1.11) |
| ≥10                         | 535/13 415         | 1.08 (0.98-1.19) | 1.08 (0.98-1.19) |
| **Daytime napping** (minutes) |                    |               |               |
| 0                           | 2446/88 980        | Reference     | Reference     |
| 1–30                        | 1167/32 709        | 1.15 (1.07-1.23) | 1.11 (1.03-1.19) |
| >30                         | 932/20 810         | 1.30 (1.20-1.41) | 1.23 (1.14-1.33) |
| **Sleep pattern ‡**            |                    |               |               |
| Healthy sleep               | 616/22 886         | Reference     | Reference     |
| Intermediate sleep          | 1104/36 831        | 1.09 (0.98-1.20) | 1.06 (0.96-1.18) |
| Poor sleep                  | 265/7433           | 1.25 (1.08-1.45) | 1.20 (1.03-1.39) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=5302).
Table S9. Hazard ratios (HRs) and 95% confidence intervals (CIs) of cardiovascular disease in relation to sleep characteristics by excluding participants with any missing values (N=7865); results from Cox models.

| Sleep characteristics          | Cases/ Person-Years | HR (95% CI) * | HR (95% CI) † |
|-------------------------------|---------------------|---------------|---------------|
| **Sleep duration (hours/night)** |                     |               |               |
| <7                            | 224/8392            | 1.23 (1.06-1.41) | 1.14 (0.98-1.32) |
| 7 to 9                        | 1502/61 943         | Reference     | Reference     |
| 9 to 10                       | 710/27 593          | 1.01 (0.92-1.10) | 1.03 (0.94-1.13) |
| ≥10                           | 219/7720            | 1.15 (0.99-1.33) | 1.07 (0.93-1.24) |
| **Daytime napping (minutes)** |                     |               |               |
| 0                             | 1540/69 354         | Reference     | Reference     |
| 1–30                          | 676/23 415          | 1.16 (1.06-1.27) | 1.12 (1.02-1.22) |
| >30                           | 439/12 878          | 1.34 (1.20-1.49) | 1.24 (1.11-1.38) |
| **Sleep pattern ‡**           |                     |               |               |
| Healthy sleep                 | 379/18 035          | Reference     | Reference     |
| Intermediate sleep            | 598/27 108          | 1.09 (0.96-1.23) | 1.07 (0.94-1.21) |
| Poor sleep                    | 141/5061            | 1.35 (1.11-1.65) | 1.27 (1.04-1.55) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=3521)
Table S10. Subdistribution hazard ratios (sHRs) and 95% confidence intervals (CIs) of cardiovascular diseases in relation to sleep characteristics; results from Fine-Gray competitive risk models.

| Sleep characteristics | Cases/Person-Years | sHR (95% CI) * | sHR (95% CI) † |
|-----------------------|--------------------|----------------|----------------|
| **Sleep duration** (hours/night) | | | |
| <7                    | 322/10 245         | 1.12 (0.99-1.25) | 1.09 (0.97-1.23) |
| 7 to 9                | 2397/79 772        | Reference       | Reference      |
| 9 to 10               | 1470/41 784        | 1.04 (0.97-1.11) | 1.04 (0.97-1.11) |
| ≥10                   | 590/14 051         | 0.99 (0.90-1.09) | 1.01 (0.91-1.11) |
| **Daytime napping** (minutes) | | | |
| 0                     | 2553/90 568        | Reference       | Reference      |
| 1–30                  | 1226/33 624        | 1.14 (1.07-1.23) | 1.11 (1.04-1.19) |
| >30                   | 1000/21 661        | 1.20 (1.11-1.30) | 1.15 (1.07-1.25) |
| **Sleep pattern** ‡ | | | |
| Healthy               | 636/23 257         | Reference       | Reference      |
| Intermediate          | 1149/37 503        | 1.07 (0.97-1.18) | 1.04 (0.95-1.15) |
| Poor                  | 280/7574           | 1.22 (1.05-1.41) | 1.17 (1.01-1.35) |

* Adjusted for age, sex, and education.
† Additionally adjusted for marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.
‡ Sleep patterns were analyzed in a subsample (n=5464).
Figure S1. Hazard ratios (HRs) and 95% confidence intervals (CIs) of the joint effect of nighttime sleep duration and daytime napping on cardiovascular disease.

Adjusted for age, sex, education, marital status, body mass index, smoking status, alcohol consumption, physical activity, type 2 diabetes mellitus, hypertension, and depression.

*P* value for multiplicative interaction was 0.740.