Intra-Individual Daily and Yearly Variability in Actigraphically Recorded Sleep Measures: the CARDIA Study

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Study Objectives: To describe the day-to-day and year-to-year variation in sleep characteristics among early middle-aged adults.

Design: Participants wore an Actiwatch (Mini Mitter, Inc) for 3 days on two occasions approximately 1 year apart.

Participants: N = 669 participants aged 38-50 years from the Chicago site of the Coronary Artery Risk Development in Young Adults (CARDIA) cohort study.

Measurements and Results: Sleep measures included sleep duration, sleep latency, sleep efficiency, and time in bed. For each sleep parameter, total variance was decomposed into between-subject variance, within-subject variance from day to day, and within-subject variance from year to year. The standard deviation was calculated from the variance. Analysis yielded a within-subject daily standard deviation (SD) of 1.26 hours and a within-subject yearly SD of 0.39 hours for sleep duration. Daily SD was 30.7 minutes and yearly SD was 6.3 minutes for within-subject variability of sleep latency. Daily SD was 8.4% and yearly SD was 2.7% for within-subject variability of sleep efficiency. Finally, daily SD was 1.31 hours and yearly SD was 0.52 hours for within-subject variability of time in bed.

Conclusions: For each of the 4 sleep characteristics, nightly variability was much greater than yearly variability, meaning sleep behavior changes little in one year in this cohort of early middle-aged adults, despite large daily fluctuations. These results have important methodological implications, including that single-day measures of sleep may not accurately reflect habitual behavior.

Keywords: Variability, measurement, actigraphy

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INTRODUCTION

WITH MOUNTING LABORATORY EVIDENCE THAT SLEEP DURATION INFLUENCES IMMUNE FUNCTION, BLOOD PRESSURE, GLUCOSE METABOLISM, HORMONAL regulation, and appetite control, and that sleep loss can lead to impairments in performance, mental health, immune function, appetite regulation, and glucose metabolism,[1-6] epidemiologists have begun to investigate sleep as a risk factor in cohort studies.[7-10] This raises the important question of whether a sleep duration measure taken at one point in time, be it a response to an interview question, a sleep log, or an objective measure using actigraphy or polysomnography, reflects habitual sleep duration or just reflects a single point in time that is not likely to be typical of a longer time horizon.

While sleep patterns are known to change from infancy to adulthood, the variability in sleep from day to day and from year to year during adulthood has not been well studied. One study examined 2 weeks of sleep diaries followed by 3 nights of polysomnography repeated after 12, 24, and 36 months in healthy elderly (>60 years).[11,12] The diary-based sleep measures showed no differences after either 2 or 3 years, and among the laboratory based measures sleep efficiency declined among subjects ≥75 years over the 2-year follow-up period, and percentage of slow wave sleep decreased for all ages after 3 years.[11,12] One study of college students observed an increase in self-reported sleep time from daily sleep logs over a spring semester,[13] while a second study observed over a spring semester a decline in time spent in bed based on sleep logs.[14] Little is known about the stability of sleep patterns from day to day and year to year among young to middle-aged adults.

The aim of the analyses presented here was to examine intra-individual variability in sleep characteristics using wrist actigraphy among early middle-aged adults over a one-year period. Our analytic approach allows us to quantify both day-to-day variability and year-to-year variability within subjects.

METHODS

Sample

These data come from an ancillary study to the Coronary Artery Risk Development in Young Adults (CARDIA) study, an ongoing cohort study of cardiovascular risk. Begun in 1985-86, CARDIA recruited adults aged 18-30 years old, balanced by sex, race (black and white), and education. A more detailed study description has been presented elsewhere.[15] This ancillary study recruited participants who were examined in 2000-2001 at the Chicago site of CARDIA. Participants in the clinical examination in year 15 of CARDIA who were not then pregnant (total eligible 814) were invited to participate in the sleep study in 2003 and 2004. All participants signed an informed written consent. The protocol was approved by the institutional review boards of Northwestern University and the University of Chicago, and by the CARDIA steering committee. The participants in this ancillary study had similar responses to a sleep questionnaire asked in the prior CARDIA interview when compared to eligible nonparticipants.[16] For example, self-reported sleep hours in the previous

Disclosure Statement

This was not an industry supported study. Drs. Knutson, Rathouz, Yan, Liu, and Lauderdale have indicated no financial conflicts of interest.

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month had a mean of 6.5 hours for both groups; 19% of participants and 20% of nonparticipants reported trouble falling asleep.[16] Therefore, participants in the ancillary sleep study appear not to have self-selected by sleep characteristics.

Sleep Measures

This ancillary study collected several sleep measures on 2 separate occasions approximately one year apart (mean ±standard deviation interval was 340 ± 73 days and ranged from 168 to 637 days). Each occasion included 3 days of wrist actigraphy (Actiwatch, Mini Mitter, Inc) and accompanying sleep log. Actiwatches use highly sensitive accelerometers to digitally record an integrated measure of gross motor activity, which is analyzed to identify sleep periods. The Actiwatch model used has an event marker button to record specific times, and we asked the participants to press this button each night when they began to try to fall asleep and again when they got out of bed each morning. The subjects were instructed to wear the Actiwatches from a Wednesday afternoon to a Saturday morning. Of the 669 subjects, 538 (80%) wore the watch on Wednesday, Thursday, and Friday in both years (6 days of data). An additional 64 subjects wore the watch for 6 days (3 days in each year) but on different days of the week in Year 1, Year 2, or both years. Also, 36 subjects wore the watch on Wednesday, Thursday, and Friday in Year 1, but did not repeat the study in Year 2, and thus only have 3 days of data. The final 31 subjects wore the watch for less than 6 days on varying days of the week: 2 subjects had 1 day, 5 subjects had 2 days, 5 subjects had 3 days, 2 subjects had 4 days and 17 subjects had 5 days.

Analysis of the actigraphy data was conducted using the manufacturer's supplied software (Actiware 3.4, Mini Mitter, Inc). The software scores each 30-second epoch as sleep or wake based on the activity counts within the epoch in question as well as in the epochs 2 minutes before and 2 minutes after the current epoch. The researcher selects the threshold for scoring an epoch as wake, and we used a medium threshold of 40 activity counts. Bedtime and wake time are set by the researcher using the event markers, sleep log, and the actigraphy data to determine these times. Sleep onset is automatically calculated by the software. It is determined by identifying the first 10-minute period of consecutive epochs in which a maximum of one epoch has an activity count greater than 2. The first 30-second epoch in this period is set as sleep onset. Sleep end is identified as the last 30-second epoch in the last 10-minute period with no more than one epoch that has an activity count greater than 2. Sleep latency is the length of time between bedtime and sleep onset. Sleep duration is the sum of epochs between sleep onset and sleep end that are scored as "sleep" according to the algorithm. This analysis includes 4 daily sleep measures calculated from actigraphy data and the sleep log: time in bed (period between bed time and wake time), sleep duration (actual sleep during time in bed), sleep latency (period between bed time and sleep onset) and sleep efficiency (percent of time in bed spent sleeping).

Statistical Analysis

The goal of this analysis was to determine the variability in sleep characteristics from day to day separately from the variability from year to year within subjects. In order to do this, our model must be able to differentiate between these 2 within-subject components of variance, and to separate those components from between-subject variability. This is formalized with the following statistical model:

$$Y_{ijt} = U_i + V_{ij} + \varepsilon_{ijt}\,, \qquad (1)$$

where Y_{ijt} represents a measured sleep characteristic on day *t* in year *j* for subject *i*. In this model, U_i represents the overall mean for approximately the past 2 years of the sleep characteristic for subject *i*. It has mean μ_{ij} and variance $Var(U_i)$. V_{ij} is the mean-zero deviation from this overall mean for year *j* for subject *i*. So, subject i's average sleep characteristic for year j is given by $U_i + V_{ij}$. Finally ε_{ijt} is the daily deviation in the measured sleep characteristic from both the overall mean and the yearly deviation. Therefore, Y_{ijt} is divided into "overall," "yearly," and "daily" components, each with a corresponding variance. Under model (1), the intra-subject correlation in yearly average sleep characteristics is given by:

$$Var(U_i) \,/\, \{Var(U_i) + Var(V_{ij})\}.$$

Models for each characteristic were estimated using restricted maximum likelihood estimation in SAS PROC MIXED (SAS Institute, Cary, NC). In these models, Ui and Vij are random effects for subject and for year nested within subject. Key advantages of using restricted maximum likelihood are statistical efficiency and the fact that, as with other likelihood-based procedures, results are valid in the presence of missing data under the missing at random assumption.[17] As such, models were estimated using all available actigraphy data.

We adjusted for race, sex, and age at first sleep measurement in our models (i.e. μ_{ij} depends on race, sex, and age). In addition, as these data typically included one weekend night for each subject, which may increase within-subject daily variability, we included a variable in the mean model identifying weekend days to adjust for weekend effects. We present our results as standard deviations and we also provide the coefficient of variation, which is the standard deviation divided by the overall mean, and allows for comparison of the variance values relative to the overall mean. Finally, since previous analysis of this data indicated race-sex differences in the 4 sleep measures,[16] we added a race-sex group effect to the random and repeated statements in our models to calculate variance values for each race-sex group separately. The significance of the race-sex differences in variance were determined by a likelihood ratio test.

RESULTS

The analysis presented here includes 669 subjects, aged 38-50 years. Fifty-seven percent of the sample was female and 44% was black. Table 1 describes the demographic characteristics of the sample and presents the means and standard deviations of the 4 sleep variables for the first year, the second year, and both years combined.

Table 2 presents the estimated year-to-year correlation, between-subject standard deviation, within-subject yearly standard deviation, and within-subject daily standard deviation for each of the 4 sleep measures. The lowest year-to-year correlation was for time in bed. Sleep latency had the highest year-to-year correlation, which was 0.93. To determine which of the 3 variability components (between-subject variance, within-subject yearly variance, and within-subject daily variance) accounted for the greatest variability, the size of their respective standard deviations were compared. For all the sleep variables, the largest standard deviation was for

Table 1—Means (standard deviation) and proportions (%) of the sample characteristics and the sleep variables from all available days of actigraphy recording.

Demographic Variables	
Age (years), Mean (SD)	42.9 (3.7)
Black (%)	44%
Female (%)	57%
Education (%)	
< High School	5%
High School	15%
Some College	28%
College Degree	25%
Postgraduate	27%
Income (%)	
<$35,000/year	34%
≥$35,000/year	66%
Employment Status (%)	
Full-time	74%
Part-time	11%
Not employed	15%

Sleep Variables Mean (SD)	**Year 1**	**Year 2**	**Overall**
Average time in bed (hours)	7.5 (1.2)	7.5 (1.3)	7.5 (1.1)
Average sleep duration (hours)	6.1 (1.2)	6.1 (1.2)	6.1 (1.1)
Average sleep latency (minutes)	22.3 (30.2)	21.7 (33.6)	22.6 (30.0)
Average sleep efficiency (%)	81.0 (10.8)	81.2 (10.6)	80.8 (10.5)

Table 2—Comparison of year-to-year correlation and standard deviations. All models adjust for age, race, sex, and weekend nights (n=667).

	Year-to-Year Correlation	**Between-subject standard deviation**	**Within-subject yearly standard deviation**	**Within-subject daily standard deviation**
Time in Bed (hr)	0.67	0.74	0.52	1.31
CV		*0.10*	*0.07*	*0.17*
Sleep Duration (hr)	0.76	0.70	0.39	1.26
CV		*0.12*	*0.06*	*0.21*
Sleep Latency (min)	0.93	22.2	6.3	30.7
CV		*0.98*	*0.28*	*1.36*
Sleep Efficiency (%)	0.90	8.1	2.7	8.4
CV		*0.10*	*0.03*	*0.10*

CV – Coefficient of Variation.

within-subject daily variance. This means that the greatest amount of variance in these 3 sleep variables was explained by day-to-day variability. For sleep efficiency, the between-subject variance (i.e., differences between individuals) was similar to but still smaller than within-subject daily variance. Within-subject yearly variance was the lowest for all 4 sleep variables. This indicates small year-to-year variability within individuals, which is also reflected in the high year-to-year correlation values discussed above.

There were significant race-sex group effects in these models according to the likelihood ratio tests, but no consistent patterns (data not shown). In general, white males and white females had lower daily variability than black males and black females. For yearly variability, white females had very little variability for time in bed and sleep duration; white males and black females had lower yearly variability for sleep latency. In general, within-subject daily variability remained highest and within-subject yearly variability remained lowest, which is consistent with the pattern seen in the full sample.

DISCUSSION

We found that year-to-year within-subject variation was low for all sleep variables in this sample: sleep duration, time in bed, sleep latency, and sleep efficiency. The greatest stability was observed for sleep latency, which had a year-to-year correlation of 0.93 and within-subject yearly standard deviation of approximately 6 minutes. The greatest variation from year to year was observed for time in bed, which had a within-subject standard deviation of 31 minutes and a year-to-year correlation of 0.67. Day to day variation was great. The within-subject daily standard deviation expresses the degree to which the sleep measure varies from day to day for a given subject in a given year. For example, the daily standard deviation was over an hour for both sleep duration and time in bed, and it was 31 minutes for sleep latency. This means that individuals differ more from day to day than they do from each other.

Only a few studies have examined intra-individual variation in sleep characteristics. These include a study of the elderly examining sleep diaries over 3 years[11,12] and a study of sleep logs among college students over a semester.[13,14] As far as we can tell, this is the first study to use an objective measure of sleep to distinguish between daily and yearly intra-individual variation in sleep. A related question that has been investigated is how many days of actigraphy are necessary to obtain reliable measures of sleep duration. For example, a study in adolescents[18] determined that a minimum of 7 days is necessary, but a study of young adult women[19] estimated that 5 nights were sufficient. We analyzed our data in a similar fashion using the Spearman-Brown formula and a reliability level of 0.7 to determine the number of days necessary for a reliable estimate of sleep duration. Analysis using all days of actigraphy data in the full sample, ignoring the yearly component, suggests that 5-6 days is sufficient for reliable measures of sleep duration in this sample of early middle-aged adults.

There are limitations to this study. Wrist actigraphy is not the gold standard measurement of sleep characteristics, but it has been demonstrated to correspond well to polysomnographic measures of sleep.[20,21] The daily variance includes measurement error, however, it is unlikely that the high daily variability observed is due to variability in the actigraphic measure itself. Data were only collected twice, about one year apart, and results may have varied if data were collected at additional time points over a longer period of time. Furthermore, not every participant wore the actigraphy monitor in the same month in both years, however, the low yearly variability suggests that seasonal differences did not greatly affect our estimates; more detailed analyses of seasonal affects on sleep and circadian timing are planned. Other study populations, involving persons of different ages or different social conditions may have a pattern of daily and yearly variability dissimilar from our sample. Therefore, the generalizability of our results to other populations may be limited. However, there did not appear to be self-selection bias relative to the larger CARDIA cohort, since participants in this ancillary sleep study gave similar responses to questions about sleep in year 15 of CARDIA compared to those who did not participate.

These results indicate that sleep duration, latency, efficiency, and time in bed, measured by wrist actigraphy supplemented with a sleep log, are quite stable from year to year in this population-based sample of adults aged 38-50 years. This finding is promising for cohort studies seeking to understand the health consequences of variation in sleep, since a single measurement period is likely similar to repeated measurement periods over a moderate time horizon, such as one year. However, day-to-day variation within subjects is very large; therefore, it is recommended that researchers record multiple days when measuring sleep characteristics. A single day will be a very "noisy" measure and only weakly reflect the multiple-day within-subject averages, whereas a multiple-day average likely reflects a true average over a longer observation window, such as one year.

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