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Sleep characteristics across the lifespan in 1.1 million the general population of the Netherlands, UK and US. A systematic-review and individual participant meta-analysis

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Abstract

Objectives. To obtain reliable reference charts for sleep characteristics in the general population across the lifespan, and to identify risk indicators of poor sleep.

Design. Systematic review and meta-analysis of individual participant data (IPD).

Data sources. Studies identified through systematic literature search in Embase, Medline and Web of Science (August 9th 2019), and through personal contacts with colleagues in the UK and US.

Eligibility criteria. Studies eligible for IPD meta-analysis had to be published between 2000 and 2017 with data on sleep characteristics assessed with questionnaires that sampled ≥100 participants from the general population of the Netherlands. Large population-based studies/surveys from UK and US were included for comparisons.

Data synthesis. For IPD analysis, data were obtained for 36 out of 47 eligible studies. Two researchers independently coded sleep variables: (time in bed (TIB), sleep duration (Total Sleep Time, TST), sleep efficiency (TST/TIB*100)), self/caregiver-reported sleep quality, insomnia symptoms and other sleep complaints, as well as socio-demographic characteristics (sex, age, education, ethnic origin, employment and partnership status) and health risk indicators (smoking and body mass index). All variables were coded following a standardized protocol. For comparison, complementary sleep data from the UK Biobank and the National Health Interview Survey in the USA were included. Where available, actigraphic sleep estimates were obtained using validated algorithms.

Results. We assembled IPD from 200,358 persons (age range 1-100 years, 55% female) from the Netherlands, 471,759 persons (40 to 69 years old, 55.5% female) from the UK, and 409,617 persons (≥18 years, 55.8% female) from the US. Age-specific percentile curves for TST demonstrate that overall 24.5% of the studied population slept less than age-specific recommendations, but only 5.8% slept outside of the “acceptable range” for sleep duration. Short sleep duration was most prevalent in teenagers, as 51.5% reported TST less than the recommended 8-10 hours and 18% report daytime sleepiness. In adults (≥18yrs), poor sleep quality (13.3%) and insomnia symptoms (9.6-19.4%) were more prevalent than short sleep duration (6.5% with TST<6 hours). Insomnia symptoms were least frequent in 26-to-40-year-olds and most frequent in persons aged >65 years, and those spending 9 or more hours in bed. Poor sleep quality was most common in those spending <6 hours in bed. Women, persons of non-European origin, overweight persons and smokers were more prone to poor sleep. While habitual TST was similar in the different countries, insomnia symptoms were between 1.5 to 2.9 times higher in USA than in the Netherlands. Women (41+) reported sleeping shorter or less efficient than men, which was opposite to actigraphy estimates where women were estimated to sleep longer and more efficiently than man, both in the UK and in the Netherlands.

Conclusion. In the largest descriptive sleep study to date, we provide age- and sex-specific population reference charts for sleep duration and efficiency which can be used in research, clinical and preventive in industrialized countries. More people report poor sleep quality than short sleep duration. Thus, whereas most available guidelines address optimal sleep duration, our findings highlight the importance of also targeting sleep quality.

Summary boxes

What is known on this topic?

-Chronic lack of sleep is an important risk factor for poor physical, metabolic, mental and social health, and well-being outcomes.

-Current recommendations focus on optimal sleep duration, but it is unclear how this relates to the prevalence of poor sleep quality in the general population.

-Sleep characteristics and problems vary with age, but no study has systematically summarized their variations and interrelations across the lifespan.

What this study adds?

-We systematically summarized variations in sleep duration, sleep timing, and sleep efficiency from age 1 to 100, to provide sex-specific population reference curves across the lifespan that might contribute to personalized sleep advice.

-Based on 200,358 individuals, persons living in the Netherlands sleep within “acceptable” sleep duration ranges across all ages, but some groups substantially deviate. For instance, one in four teenagers sleeps almost an hour less than recommended.

- Adults that spend 7 to 8 hours in bed report the least sleep problems. Those spending less than 6 hours in bed commonly report poor sleep quality, while those spending more than 9 hours in bed have more problems with sleep initiation.

- While self-reported sleep duration in adult populations from the Netherlands, UK and US is similar, insomnia symptoms are more prevalent in the US than in the Netherlands.

- Women report less optimal sleep duration and efficiency than men, but according to actigraphy-estimates women sleep longer and more efficiently that man.

- Sleep duration of at least 7 hours per night are guidelines suitable for subjective sleep reports but not actigraphic sleep estimates, because more than 80% of the adults over 40 years have actigraphically estimated TST below recommendations. Recommendations for actigraphy-estimated sleep are currently lacking.

- Consistent across studies and countries, poor sleep quality is a greater perceived problem than short sleep, a finding that calls for targeting sleep quality improvement.

Keywords: Sleep, Sleep Wake Disorders, Dyssomnias, Sleep Initiation and Maintenance Disorders, epidemiology, population-based, Individual Participant Meta-analysis, population reference values

Abbreviations: Body mass index (BMI), difficulty initiating sleep (DIS), difficulty maintaining sleep (DMS), early morning awakenings (EMA), individual participant data (IPD), sleep quality (SQ), TIB (Time in Bed), TST (Total Sleep Time), SE (Sleep efficiency)

Introduction

Poor sleep is common and increasingly recognized as a potentially modifiable risk factor for various physical and mental health problems.(1, 2) Yet, sleep has received little attention from a public health perspective. This may partly be due to the lack of valid descriptions of typical sleep patterns in the general population. Estimating reference ranges for sleep variables can help quantify the sleep problem at a population level and define the public health challenge.

The widely used sleep duration recommendations issued by the American National Sleep Foundation (NSF)(3, 4), synthesize relevant empirical studies but partly rely on expert opinion, thus may differ from data-driven descriptions of sleep in the general population.(5) In addition, these recommendations target healthy populations, whereas the general population represents the continuum between health and disease. It is also unclear how the three categories of sleep duration (recommended, acceptable, not recommended) relate to sleep quality or other sleep complaints. Ideally, recommendations for sleep duration in the general population should be described over multiple physiologically and clinically relevant aspects, including age, sex, demographics, or lifestyle. We described variations in sleep duration and estimated the proportion that falls outside of the recommendations, and studied factors related to suboptimal sleep.

Few epidemiological studies have systematically summarized sleep characteristics in the general population. The studies conducted to date have either collected data via mobile devices(6) or online surveys,(7, 8) have focused on a particular age group such as children(9, 10) or older adults,(11, 12) or studied a single sleep problem such as short sleep(13), long sleep or insomnia(14, 15). We summarized available information in the general population by jointly investigating multiple sleep variables

across the lifespan. Importantly, as opposed to previous meta-analytical efforts (16-18), also of similar sample sizes (19), we assembled individual participant data (IPD) from 200,358 persons aged 1 to 100 years, from 36 population-based studies from the Netherlands. This allowed us to explore sleep characteristics in various subgroups as well as interrelations between sleep indices. In addition, we compared the available estimates with those from two large population-based adult samples from the UK (n=498,320) and USA (n=409,617).

This study provides reliable estimates of self-reported sleep duration, sleep timing, sleep efficiency, but also perceived sleep quality, insomnia symptoms and other sleep complaints (non-restorative sleep, sleepiness, snoring and use of sleep medication) in the general population. In order to obtain valuable population percentile curves and reference values we described these variables across age and sex. We also explored educational level, ethnic origin, partnership and employment status, as well as BMI and smoking, as potential risk indicators associated with these sleep variables. Where data was available, we complemented subjective data with objectively estimated sleep variables. Moreover, we evaluated consistency and differences in sleep parameters across populations from the Netherlands, UK and USA.

Methods

Search strategy, eligibility and selection criteria

We conducted a systematic literature search to identify population-based cohorts from the Netherlands assessing sleep characteristics via questionnaires. We searched Embase, Medline Ovid, and Web of Science Core Collection on August 9th 2019 with a search strategy developed by a biomedical information specialist (WB; Supplementary Text). Inclusion criteria were: i) population-based sample from the Netherlands; ii) inclusion of at least 100 participants older than 1 year; iii) assessment of sleep with questionnaires; iv) publication in a peer-reviewed journal after the year 2000. Exclusion criteria and steps are outlined in a detailed flowchart (Supplementary Figure 1a and 1b). All 5,750 identified abstracts were checked for eligibility by two independent reviewers (DK and either TSL, YX, MEKV or ID, references were split randomly), after which DK assessed 381 full-text articles for eligibility, and TSL again assessed the excluded articles. From 142 publications that met our inclusion criteria, we identified 43 non-overlapping study populations. We additionally added 4 studies identified by personal contacts, but sought IPD from 47 studies (IPD was not requested from 3 studies that were published after data collection had been completed in early 2017), of which 36 agreed (response 81%). From studies with repeated measurements, the baseline measurement was used for this IPD as it comprised the largest sample size.

All studies included in the meta-analysis (Supplementary Table 1) were approved by the ethics committee of the local university, institute or organization. Written informed consent was obtained in the original studies from all participants or caregivers (see publications in Supplementary Table 1). The first and corresponding authors obtained legal rights for access to anonymized datasets. This article follows the Preferred

Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for Individual Patient Data reporting guidelines, Supplementary Text 2.(21)

To evaluate consistency of sleep characteristics across countries, we included two large population-based datasets from adults in the UK Biobank (n=498,320) and the National Health Interview Survey (NHIS) from the USA (n=409,617).

Patient and Public Involvement

This research is a response to public interest. In April 2015, residents of the Netherlands were asked to indicate which scientific questions should be addressed in the next decade. Requests of 11,700 people laid the foundation for the National Science Agenda (https://wetenschapsagenda.nl/). Text analysis revealed that attention for sleep-related issues was requested 423 times; hence the current research question can be considered relevant by the general population. However, participants were not invited to comment on the study design or interpretation of the results. Participants did not contribute to the writing or editing of this document for readability or accuracy.

Individual Participant Data coding

To maximize internal validity, we harmonized the datasets in a three step procedure: 1) we agreed upon definitions for each sleep variable (described in the Coding Steps and Protocol, see Supplementary Text), also socio-demographic variables were classified in line with Statistics Netherlands.(22, 23); 2) two independent coders (DK and TSL) coded all datasets according to the standardized protocol (reliability statistics reported in Coding Steps and Protocol); and 3) coding disagreements were resolved by consensus supervised by a senior sleep researcher (HT).

Sleep variables

We distinguished the following 10 sleep variables:

- *Time in bed (TIB, hours)* was calculated as the difference between *bedtime* and *wake up time* in hours, for weekdays and weekends separately. Bedtimes between 12:00 and 17:00, and wake up times between 17:00 and 02:00 were excluded (N=97).
- *Sleep duration (Total Sleep Time, TST, hours)* was self- or caregiver-reported, values ≤2h or ≥20h were excluded (N=81).
- *Sleep efficiency (SE, %)* was calculated as (TST/TIB)*100. Note that TST and bedtimes/waketimes were assessed separately, which may result in implausible values, e.g. TST of 7.5, and TIB between 11pm and 7am results in implausible SE, but likely represents high SE. To balance bias in estimates with loss of precision: values between 100% and 110% were recoded to 100% (mainly errors in reporting times, n=7,630, 8.8%), values above 110% were excluded (n=2,597, 2.9%, most from the largest cohort, Lifelines Study).
- *Daytime napping* was defined as reporting ‘regularly’ or ‘frequently’ sleeping ≥30min during the day (yes/no).
- *Insomnia symptoms* (yes/no) included difficulty initiating sleep (DIS), defined as trouble falling asleep (≥30 minutes); difficulty maintaining sleep (DMS), defined as trouble falling asleep again after nocturnal awakening; and early morning awakening (EMA), defined as waking up earlier than desired and not being able to fall asleep anymore. Insomnia symptoms were present if symptoms were reported to occur often, frequently, or ≥3 times per week.(24)
- *Sleep medication* was defined as the reported use of any medication to aid sleep at least once a week (yes/no).

- *Non-restorative sleep* was defined as not feeling rested when waking up in the morning, reported at least 'often' or ≥3 times per week (yes/no).
- *Sleepiness* was defined as 'feeling sleepy' during the day, reported at least 'often' or ≥3 times per week (yes/no).
- *Snoring* was present if snoring was reported at least once a week (yes/no).
- *Poor sleep quality* was present if any questions on how individuals perceived or judged their habitual sleep were answered with "bad", "unsatisfactory", "insufficient", or similar qualifications (yes/no).

Socio-demographic variables

Ethnic origin was based on self-report on the country of birth of the participant and his/her parent(25) and categorized into European origin - Dutch, European origin – other, and non-European origin.(23) Educational level was based on self-reported highest education and categorized into low (lower vocational training, or ≤3 years at general secondary), medium (>3 years general secondary school, intermediate vocational training or first year of higher vocational training), or high (university degree, higher vocational training).(22) Having paid employment and having a partner (including non-cohabiting) were self-reported and classified as yes/no.

Health risk indicators and lifestyle variables

Smoking was self-reported and categorized into: never, former, or current smoker. BMI (kg/m^2) was calculated based on self-reported or measured weight and height. BMI from 18.5 kg/m^2 to 25 kg/m^2 was defined as normal weight. Underweight was defined as BMI below 18.5kg/m^2, overweight as BMI above 25 kg/m^2 and obese above 30 kg/m^2. These variables were only defined for adults.

Complementary objective sleep estimates

In two cohorts from the Netherlands, subjective sleep reports were collected simultaneously with sleep diaries and actigraphy. In the Generation R Study children aged 10-15 years (n=1386) wore Geneactiv watches during 9 days.(26) In the Rotterdam Study participants aged 45-98 years (n=1940) wore Actigraphy watches during 7 days.(27) Actigraphic sleep variables were estimated with validated algorithms. Actigraphy and diary sleep estimates were averaged across days. The actigraphic sleep variables were complemented by those of 85,499 participants from the UK Biobank (UKBB).(28)

International comparisons

To evaluate consistency across countries, the IPD analyses were complemented by data from international cohorts. First, the UK Biobank (UKBB) (www.ukbiobank.ac.uk) is a large population-based cohort study aimed at improving prevention, diagnosis and treatments of various illnesses. Between 2006 and 2010, approximately 9.2 million people aged 40-69 years were invited. Second, US data were obtained from the National Health Interview Survey (NHIS, https://www.cdc.gov/sleep), harmonized by Integrated Public Use Microdata Series (https://nhis.ipums.org/nhis/), a nationally representative survey of non-institutionalized American adults surveyed annually (2004-2017). We included adults aged 18-84 years with non-missing responses for the respective sleep measures.

In the UKBB, adults reported on TST by answering the question “About how many hours sleep do you get in every 24 hours? (please include naps)”. We excluded participants reporting usual daytime napping from the UKBB (n=26,561). NHIS participants answered the question “On average, how many hours of sleep do you

get in a 24-hour period?", with responses in hour increments. Symptoms of insomnia in the UKBB were assessed by the question: "Do you have trouble falling asleep at night or do you wake up in the middle of the night?", which did not map on any of our individual insomnia constructs, thus was not further analyzed. NHIS participants reported DIS and DMS using two questions: "In the past week, how many times did you have trouble falling asleep?" and " In the past week, how many times did you have trouble staying asleep?", respectively. Participants that reported having these symptoms "usually" in the UKBB, and "≥3 times per week" in the NHIS were coded as "yes". These estimates were compared to the pooled IPD meta-analysis sample.

Statistical analyses

We explored whether the population in the meta-analysis was representative of the general population of the Netherlands by comparing the distributions of age, sex, and education with the last Dutch Census in 2011.(29) For descriptive purposes, we pooled the data across studies, with different studies contributing data for different sleep variables, according to what data had been collected.

First, age and sex specific means and prevalences of sleep variables were computed based on systematically coded variables to reduce between-study heterogeneity (see Coding Protocol in Supplementary Text). Age categories were aligned to those of NSF: toddlers (1-2 years), preschoolers (3-5 years), school-aged children (6-13 years), teenagers (14-17 years), young adults (18-25 years), adults (26-40 years), middle-aged adults (41-64 years), and older adults (65+ years).

Second, variations in TST, SE, and TIB were plotted using age-specific percentiles (10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th}). To facilitate comparison, TST was also plotted against the NSF sleep duration recommendations: 11-14h for toddlers, 10-13 hours for

preschoolers, 9-11 hours for school-aged children, 8-10 hours for teenagers, 7-9 hours for adults 26-64 years old and 7-8 hours for older adults.(3) To explore detailed age-related changes in TST, SE and TIB we also estimated percentile curves against continuous age between 1 and 100 years using *gamlss* R package.

Third, we examined associations of sleep duration, sleep efficiency and insomnia symptoms with socio-demographic and health indicators using one step approach. We used linear mixed models, with a random intercept for each study to account for between study heterogeneity. In these analyses, we only included participants aged 18 years and older as sleep characteristics change rapidly during childhood and adolescence.(9) Three models were constructed: a “demographic determinants model” where we studied the association of mutually adjusted age (continuous), sex, educational level and ethnic origin with sleep variables, a “social determinants model” where we studied the association of employment status and partnership on sleep variables adjusted for demographic determinants, and a “health indicators model” where we studied the association of smoking and BMI with sleep variables adjusted for demographic determinants.

As more sophisticated imputation methods cannot account for within-study clustering, missing values on age (0.3%) were imputed with the study-specific mean, and a missing category was used to account for missing values in categorical variables (education=0.6%, ethnic origin=26.6, employment=7.4%, partner=62.2%, smoking=15.0%, BMI=13.3%). Ethnicity was not assessed in 8 studies, whereas of the studies in adult populations five did not assess employment and three did not assess smoking. Missing or implausible values on sleep variables were not imputed. Data were analyzed using *SPSS Statistics,* version 21 (IBM Corp., Armonk, NY) and R version 3.4.1.

Results

We included 34 studies, identified by systematic review, including 200,358 participants from the Netherlands between the age of 1 and 100 years. Additionally, 471,759 persons (40 to 69 years old, 55.5% female) from the UK, and 409,617 persons (≥18 years, 55.8% female) from the US were included. Population characteristics of the studies identified in the systematic review are presented in Supplementary Table 1. Compared to data of the 2011 Dutch Census,(29) females in age groups between 10 to 80 years were slightly over-represented (ranging from a 1% to 9% difference). Persons in both the high (29.9% vs, 29.0%, p=0.013) and the middle (37.3% vs. 34.4%, p<0.001) educational level were slightly overrepresented in our sample, compared to the population described in the Dutch Census of 2011. Study specific sleep estimates are provided in Supplementary Table 2.

Time in bed, sleep duration and sleep efficiency

Adults (≥18 years) reported a mean±SD TIB of 7.8±0.9 hours, a TST of 7.1±1.0 hours, and a SE of 89±9% (Table 1). Short sleep duration (TST<6 hours) was reported by 6.5% of this population, whereas 25.8% reported a TST of <7 hours. Population percentile curves of TST and SE across age categories defined by NSF recommendations are shown in Figure 1, and in Supplementary Figure 2 for age (continuous). Although 24.5% of the population sleeps less than the recommended sleep duration for age, only 5.6% fall outside of the “acceptable” ranges (see Supplementary Table 3). More than half (51.5%) of 14-to-17-year-olds reported sleeping less than recommended 8-10 hours per night; those in the 25th percentile sleep 54 minutes less, whereas those in the 10th percentile sleep 96 minutes less than recommended. In all other age groups, even the 5% and 95% percentile groups, sleep duration was in the “acceptable range” as defined by the NSF (3). SE

decreases from mean±SD= 97±5% in childhood to 91±8% in teenage years. This SE decline continues into adulthood, however 25% of >65-year-olds reported sleeping over 95% of their TIB.

Sex difference were observed from adulthood onwards (Table 1). Adult women reported a longer TST (B=0.14 hours, 95%CI: 0.18;0.21, p<0.001), but a marginally lower SE (B=-0.02%, 95%CI: -0.03;-0.02, p<0.001) than men (Supplementary Table 4). For example, women between 41 and 65 years of age sleep on average 7.1±1.1 hours, whereas at the same age men sleep on average 6.9±1.0 hours per night. However, the women sleep 89±10% of the TIB, whereas men sleep 92±9% of the TIB. From about 14 years onwards, the between-person variation in TIB increases substantially, more so for men than for women (Figure 2). Sex-specific TIB percentiles using age (continuous) are shown in Supplementary Figure 3. From 14 years onwards bedtime is gradually delayed, whereas wake time remains stable around 7:00h across the lifespan (Figure 3). Poor sleep quality is most prevalent in persons (≥18 years) spending <6 hours in bed, whereas difficulty initiating sleep is most commonly reported by those spending ≥9 hours in bed (Figure 4).

We found that TIB is longer on weekend days than on weekdays only for age groups that go to school or work. In young children and older adults, the TIB on week- and weekend days is roughly equal. The weekday-weekend difference increases as children start going to school (median difference of 30 minutes), peaks in teenagers (median difference of 75 minutes), and is around 60 minutes in working adults.

Daytime Napping

As expected, most children nap in the first 3 years (80% of 1-2 year-olds, 65% of 3 years-old). Napping is less common during school age (12.7% of 6-13 year-olds nap)

and adulthood (13.7% of people between 26 and 64 years nap regularly), than in persons aged >65 years (27%).

Insomnia symptoms

Symptoms of insomnia increase from childhood (3 to 5 year-olds: 4% DIS, 6% DMS) into adolescence (6-13 year-olds: 13% DIS, 9% DMS). In adulthood, insomnia symptoms are least frequent in 26 to 40-year-olds and most frequent in >65-year-olds. DIS is most prevalent in 18 to 25-year-olds (22.6%), whereas DMS (23.2%) and EMA (23.5%) are most prevalent in the >65-year-olds. Sex difference in insomnia symptoms become evident only in puberty (i.e. for 14 to 17 year olds, Males vs. Females: 12% vs. 19% DIS, 16% vs. 28% DMS). In adults, women are at increased odds for DIS (OR=2.26, 95% CI 2.16;2.36), DMS (OR=2.05, 95% CI 1.91;2.19), or EMA (OR=1.49, 95% CI 1.37;1.62; Supplementary Table 5) compared to men after adjusting for demographic factors.

Other sleep complaints

Sleepiness is most prevalent in teenagers (20.4%; Supplementary Table 6). Although there are no clear sex difference in sleepiness, non-restorative sleep is more prevalent in women than in men. Women also use sleep medication more often (8.6% vs. 5.2% in 26 to 40-year-olds, to 17.5% vs. 6.3% in >65-year-olds). Snoring is more commonly reported in adult men than in women (40.2% vs. 23.2%), although this difference becomes less pronounced at older ages (Supplementary Table 6).

Associations of socio-demographics with sleep characteristics in adults

Adults with a low educational level did not differ in TST (B=-0.01 hours, 95%CI -0.02;0.00, p=0.191) compared to highly educated adults, but reported a slightly lower

SE (B=-0.01%, 95% CI -0.03;-0.00, p<0.001). In addition, persons with a non-European ethnic origin sleep shorter (B=-0.30 hours, 95%CI: -0.34;-0.30, p <0.001), and less efficiently (B=-0.03%, 95%CI: -0.03;-0.02, p<0.001) compared to persons with Dutch ethnic origin. Similarly, both low education and non-European ethnic origin were risk indicators for insomnia symptoms (Supplementary Table 5). Having paid employment and a partner were both associated with longer sleep duration and less insomnia symptoms, independent of demographics (Supplementary Table 4 & 5).

Association of health risk indicators with sleep characteristics in adults

In adults, we observed shorter TST for overweight (2.4 minutes, 95% CI: 3.6;1.8) and obese persons (6.6 minutes, 95% CI: 7.2; 5.4), compared to persons with normal weight. Obese, but not overweight persons, had a marginally lower SE (B=-0.004%, 95%CI: -0.01; -0.00) and experienced more DIS (OR=1.08, 95%CI: 1.02; 1.17; Supplementary Table 4). Both former and current smokers reported sleeping shorter relative to non-smokers, and current smokers also reported a lower SE. Current smokers experienced more DIS, but experienced less DMS (Supplementary Table 5).

Complementing subjective with objective sleep data

TIB and TST were between 0.4-1.9 hours shorter when estimated with actigraphy as compared to sleep diary reports of the same nights (Supplementary Table 7). Similarly, actigraphic SE estimates were lower compared to diary estimates, averaging to 9.7±7% difference in the Generation R sample, and 9.6±9% difference in the Rotterdam Study sample. The sleep diary SE estimates were also lower than those computed from the pooled IPD, except for the group of teenagers where SE based on pooled IPD was estimated to be 91±8%, as compared to 95.6±4% estimated by sleep diary. According to actigraphic TST estimates, more than 80% of

the population, sleeps less than the US recommendations (Supplementary Table 8). The proportion of persons sleeping less than the “acceptable” TST ranged between 16.3%-38.7% in the pediatric cohort, and between 9.4%-47.3% in the older adults, as measured with actigraphy. Actigraphic sleep parameters of the adults from the Netherlands were compared with respective values from adults in the UK (Supplementary Table 9). Both TIB and TST were ≥1 hour longer in the UK cohort regardless of age and sex, however SE differences were small (1.6% to 2.1%). Women (41+ years) reported sleeping shorter and/or less efficiently than men both in sleep diaries and sleep questionnaires, whereas actigraphy estimates indicate the opposite: women sleep longer and slightly more efficiently than men of similar age (Supplementary Table 7). This was also found in the UKBB cohort.

International comparisons

Average self-reported TST as well as sex difference in TST were similar in the adult Dutch, UK and US populations (Supplement Table 10). The proportion adults reporting TST shorter than recommended for age was the highest in the US (30.3%), compared to 24.5% in the Netherlands, and 25.0% in the UK. The proportion of adults sleeping less than the “acceptable” values were below 10% in all three countries. The prevalence of insomnia symptoms (Supplementary Table 11) was 1.5 to 2.9 times higher in the US sample (for DIS and DMS, across adult ages with the exception of 18-25 year olds) than in the Netherlands. Sex and age differences in insomnia symptoms were similar across populations: DIS reduced and DMS increased with advanced age, whereas women reported insomnia symptoms more commonly irrespective of age.

Discussion

Our results suggest that: i) the population of the Netherlands reported sleeping within "acceptable" sleep duration range at all ages, but more than half of teenagers slept almost an hour less than recommendations; ii) actigraphic sleep duration and efficiency are consistently lower than self-reported estimates, which limits the applicability of current recommendations to objective sleep variables, iii) insomnia symptoms were least frequent in 26 to 40-year-olds and most frequent in persons aged >65 years, and those spending 9 or more hours in bed; iv) self-reported TST did not differ substantially between adults from the Netherlands and from the UK and US, but insomnia symptoms were 1.5 to 2.9 times more prevalent in the US than in the Netherlands, v) poor sleep quality and insomnia symptoms were more prevalent than short sleep duration; vi) women, persons of non-European origin, overweight persons and smokers were particularly prone to experiencing poor sleep.

Strengths and weaknesses

Our study is the largest descriptive sleep study to date. However, several methodological issues must be discussed. First, variables such as sleep timing and duration may be more objectively assessed with actigraphy or polysomnography.(30, 31) However, subjective complaints are clinically relevant, and highly related to daily functioning. Moreover, the implementation of measures such as polysomnography in large-scale population-based studies is currently limited. In this study we were able to complement subjective data with objective sleep parameters in teenagers and older adults. These are the two age groups with the highest prevalence of insufficient sleep duration. Sleep duration estimates differ by method of assessment, but habitual sleep duration is reasonably stable within individuals.(32, 33) Thus, the inter-individual differences in sleep duration can reliably be compared when assessed with the same

method only. Moreover, absolute numbers should be interpreted with caution because age or reporter could influence sleep estimates (e.g. parents may underreport their children's sleep onset latency and wake time during the night, resulting in higher SE estimates). Second, heterogeneity between studies could have introduced misclassification bias (e.g. different definitions of bedtimes and waketimes can influence TIB estimates). However, access to IPD improves data quality through standardization of definitions. Third, we could not assess potential confounding by underlying sleep disorders (e.g. sleep apnea), psychiatric disorders, other chronic medical conditions that could disturb sleep and the ability to go out of bed, environmental or occupational factors (noise, shift work). Fourth, although we studied a representative large population sample of the Netherlands, and compared sleep estimates to other populations from developed countries, findings may not be generalizable to populations with different sociodemographic or cultural characteristics. These international comparisons were possible for some sleep parameters only. However, all studies sampled participants from the general population, which reduces the chance of selection bias, and increases the interpretability of the comparisons.

Comparison with other studies

In our study, 25% of the adult population reported sleeping less than the recommended 7-9 hours, whereas the Centers for Disease Control and Prevention has estimated up to 44.1% of the US population aged ≥18 years slept less than 7-9 hours.(34) We showed that the average self-reported sleep duration does not differ between the Netherlands, US and UK, but the prevalence of sleeping below the recommended TST was higher in the USA population (30%), than in the European populations (24-25%). We also showed that the recommendations are only

applicable to subjective sleep reports. Specifically, 80% of participants above 40 years, have an actigraphic TST less than the “recommended” 7 hours TST. It is important to note that a portion of this population still falls within the “acceptable” range of 6 to 11 hours developed by the NSF expert panel (3, 4). The pooled IPD data show that 6.8% of the adult population report sleeping less than the “acceptable” 6 hours, but this increased to 25% at an older age. Using actigraphic TST estimates up to 47% adults were estimated to sleep less than the “acceptable” values. Based on an online questionnaire, Kerkhof has reported a higher percentage (30.4%) of <6 hours of sleep in an adult population from the Netherlands.(7) Studies included in our meta-analysis have shown that participants aged 18-65 years old sleeping both less than 6 hours (35) and less than 7 hours(36) per night have higher cardiovascular risk as compared to those sleeping 7 to 8 hours per night. A Time Use Survey Panel in industrialized countries in Europe and North America (37) has also shown that older adults sleeping <7 hours have lower self-reported health, although the “acceptable” sleep duration for this age group can be as short as 5 hours per night. It thus remains unclear what the appropriate amount of self-reported sleep duration is for preserving health, and reference values for objective sleep duration are merely unknown. Despite the premise that ‘optimal’ sleep duration likely differs per outcome, providing reference values can be useful in clinical or prevention practice. This way it is possible to estimate the extent of the problem (i.e. the proportion that falls outside of recommended values) which could guide public health policies for improving sleep in the general population. Therefore, we estimated sleep duration percentile curves, which to date have been estimated only in children and adolescents (9, 10, 38). Healthcare professionals can easily assess sleep characteristics by interviews or questionnaires, but with increased use of

accelerometers in research and daily settings, reference curves for actigraphic sleep variables should also be estimated.

Several previous observational studies have estimated the prevalence of insomnia in European populations (7, 11, 14, 15, 20). Our study estimates (7 to 23% depending on insomnia symptom and age group) largely correspond with those reported in telephone interviews by 25,579 persons from seven European countries in the 90's (14). The prevalence of DIS and DMS in the Netherlands, however, was substantially lower than in the US. Our study, adds age-specific information on the prevalence of insomnia symptoms across the lifespan, and shows which insomnia symptoms are most common in each age group. We also show that these age related changes in insomnia symptoms are similar in the USA. This information could be used to improve sleep on a population level, i.e. young adults would likely benefit from interventions tackling difficulty initiating sleep, whereas older adults might need help with sleep maintenance or early morning awakenings. We also show that spending 7 to 8 hours in bed is associated with better sleep quality and fewest insomnia symptoms, similar to a general-population study in Norwich, UK (11).

In line with previous reports based on smaller samples, we found using pooled IPD data that women report longer sleep duration but lower sleep efficiency (7, 11). For example, a 28-year-old woman reporting to spend 9 hours in bed is in the 90th percentile of the female population of similar age, whereas, a 28-year-old man with the same TIB, would be in the 95th percentile of the male population of similar age. When measured with actigraphy, however, women's sleep was slightly longer and more efficient than that of men in the Netherlands and in the UK. Women experience more insomnia problems than men in all three countries. This commonly reported difference (7, 14, 20, 39) emerges during puberty, suggesting sex hormones, among

other social factors such as stress or parenting, might play a role in the development of insomnia problems. Interestingly, women do not report daytime sleepiness more often, despite experiencing more insomnia problems and using more sleep medication than men.

Relevance of the study

The estimated population reference charts for sleep timing, sleep duration and efficiency across the lifespan, will help guide personalized advice on sleep duration. However, current recommendations are applicable only to self-reported average sleep duration. Given that poor sleep (i.e. low sleep quality or insomnia symptoms) is more common than short sleep (i.e. TST below “acceptable” values) in Europe and in the US, recommendations for improving sleep might need to focus on sleep quality. Importantly, we identified subgroups that are prone to short or inefficient sleep, such as teenagers, women, persons of non-European origin, obese and smokers. These population strata could be used as sampling schemes when developing interventions to improve sleep at a population level. We also show that the lowest prevalence of poor sleep in the general population occurs in those spending 7 to 8 hours in bed. This finding, taken together with the relatively high prevalence of poor sleep despite close to appropriate sleep duration, warrants towards defining new targets for sleep hygiene advice. In other words, by recommending optimal sleep duration we are unlikely to accomplish better sleep at a population level.

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Contributors

DK, HT & EVS designed the study and together with TSL and AIL worked on establishing definitions, and obtaining contact with the included cohorts and drafting the manuscript. OHF provided expertise in systematic reviewing and meta-analysis; WMB provided systematic literature reviewing of online databases expertise. DK, TSL, ID, MEK-V, YX independently screened abstracts identified by systematic review. DK, TSL, MPCML and AIL closely monitored data coding and ensured reliability. DK and TSL independently coded all individual datasets, and DK analyzed the data. All other authors were involved in the design, data collection or management of the individual studies, and provided important insight into the respective datasets and their coding, cleaning and usage. All authors critically evaluated the manuscript and approved the last version.

Transparency statement: The corresponding author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; and that no important aspects of the study have been omitted.

Data sharing: Coding protocol for data analysis is provided in the appendix. Our data protection agreements with the participating cohort studies do not allow us to share individual-level data from these studies to third parties.

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