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Measuring Sleep Efficiency: What Should the Denominator Be?

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Inconsistency in operationally defining sleep efficiency (SE) creates confusion with regard to the conceptualization and use of the construct by researchers and clinicians. The source of the inconsistency is the denominator of the widely published operational definition of SE: ratio of total sleep time (TST) to time in bed (TIB) (multiplied by 100 to yield a percentage). When taken literally, TIB includes non-sleep-related activity (e.g., reading, texting, conversing with a partner, watching television) both prior to initiating sleep and after the final awakening. However, the construct of SE refers to TST compared to the amount of time spent attempting to initially fall asleep and sleep discontinuity. Non-sleep related activities in bed do not reflect that construct. Also, time *out of bed* during nighttime awakenings, a manifestation of sleep discontinuity, should be included in the SE denominator. Using TIB as the denominator can also create a methodological problem when SE is an outcome measure in sleep intervention research. It is proposed that research and practice would benefit by clarifying and adopting a consistent operational definition that more accurately captures the construct of SE. An alternate denominator, duration of the sleep episode (DSE), is suggested, where DSE = sleep onset latency (SOL) + TST + time awake after initial sleep onset but before the final awakening (WASO) + time attempting to sleep after final awakening (TASAFA). The proposed formula for SE would be: SE = TST / DSE (× 100). DSE can be easily calculated using standard sleep diary entries along with one item from the Expanded Consensus Sleep Diary. Implications for insomnia research and practice are discussed.

Keywords: insomnia, sleep efficiency, time in bed

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INTRODUCTION

Sleep efficiency (SE), commonly defined as the ratio of total sleep time (TST) to time in bed (TIB), plays a central role in insomnia research and practice. The significance of SE is understandable because it captures a core problem for those suffering from insomnia—spending too much time in bed trying to sleep. The struggle to sleep is associated with psychological distress prior to sleep, while trying to sleep, and during regular waking hours, all of which perpetuates the problem of insomnia.[1,2] Improvement in SE has thus become a gold standard for evaluating insomnia treatment efficacy. Behavioral clinicians also use SE when implementing sleep restriction therapy (SRT), a standard component of cognitive behavioral treatment for insomnia (CBT-I).

While the concept of SE seems clear, the literature reveals inconsistency in how SE is operationally defined. For example, a recent meta-analysis of polysomnographic sleep studies reported that only 6 of 18 studies explicitly defined SE as the ratio of TST/TIB.[3] Eleven studies did not specify a definition of SE, and one defined it as TST/total recording time. Given the importance of SE to sleep research and practice, a focused discussion of the conceptualization and operationalization of sleep efficiency may be useful to both sleep researchers and clinicians.

CONCEPTUAL AND OPERATIONAL DEFINITION OF SLEEP EFFICIENCY

A conceptual definition of SE can be inferred from early publications. Perlis et al. define SE as "sleep continuity."[4] Spielman et al. offer a more nuanced conceptualization, writing that SE "…reflects difficulty in falling asleep as well as difficulty staying asleep and is therefore generally applicable to patients with different insomnia complaints…"[5] These statements suggest that the denominator in the SE equation should not be TIB, but rather the time span that begins with the initial attempt to sleep and ends when the person finally wakes and no longer attempts to sleep. As such, the denominator should *exclude* non-sleep related activities that occur in bed prior to attempting to sleep and those that occur after finally waking (e.g., reading, texting, conversing with a partner, watching television, engaging in sex, daydreaming). The denominator should also *include* time awake during the middle of the sleep attempt episode, regardless of whether it is spent *in or out* of bed.

Given that SE is consistently defined in the literature as the ratio of TST/TIB,[6] it is not surprising that most studies operationally define the denominator literally as the total amount of time in bed, rather than the time of intended sleep. For example, Petrov et al. measured SE by the "proportion of time slept to time spent in bed."[7] Matthews et al. assessed SE using the "ratio of total sleep time to actual time in bed × 100."[8] In Visser et al., habitual SE was based on "a calculation of the amount of time spent sleeping compared with the amount of time spent lying in bed."[9] A meta-analysis of self-help therapy for insomnia defines SE as "percentage of time slept of the total time spent in bed."[10]

Some studies have more closely captured the concept of SE by excluding from the denominator some or all of the time in bed engaged in non-sleep related activities. For example, Palesh et al. operationally defined SE as "the ratio of total sleep

time to total sleep time plus *wake after sleep onset* (emphasis added)."[11] While this definition eliminates non-sleep related activity prior to sleep onset, it excludes time attempting to initially fall asleep (sleep onset latency). Kushida et al. used the formula: (SE = [total sleep time / total recording time] × 100), with recording time beginning with "lights out" and ending with "lights on."[12] Similarly, Jacobs' self-help book defines the denominator, TIB, as the "time elapsed from "lights out" at bedtime until you rise in the morning."[13] Ambiguity remains in the latter two definitions insofar as a literal translation of "lights out" does not preclude non-sleep related activities while the lights are out. In addition, both studies fail to account for time lying in bed with lights out after the final intended awakening. In each case, there exists the needless possibility of imprecision.

Adding to the confusion, in calculating TIB most researchers and clinicians add the amount of time awake during the middle of the night, regardless of whether it was spent *in or out* of bed.[5] These awakenings reflect sleep discontinuity regardless of where they occur, and therefore they should be allocated to the denominator in the SE equation. The confusion exists because the term TIB itself is a misnomer.

A discussion of SE measurement requires attention to stimulus control therapy (SCT) and sleep restriction therapy (SRT) techniques, both commonly employed in CBT-I. The SCT procedure instructs participants to limit TIB to sleeping and sex. SRT prescribes a specific time to commence the sleep process and to awaken. If a participant fully complies with these techniques, the amount of TIB engaged in non-sleep related activities should be virtually nil (with the exception of time engaged in sex), and thus the measurement concerns raised above are considerably lessened. Hence, Perlis et al., operationally define TIB as the difference between "prescribed time to bed" and "prescribed time out of bed."[4] However, it is not feasible to adopt an operational definition based on "prescribed TIB" because its accuracy assumes full compliance with the prescription, which is highly unlikely. This definition also cannot be used for baseline measurements of SE, which would occur prior to the prescription.

Progress in sleep research and treatment is likely to be hampered until SE is consistently measured in a way that precisely captures the conceptual definition of SE. The concept of SE refers to the ratio of total sleep time relative to the time span that *begins* when the person engages in behaviors that are intended to induce sleep (e.g., lying still, eyes closed) and *ends* when the person finally wakes *and* ceases all further attempts to sleep even if they remain in bed. This time span includes temporary unintended middle-awakenings, regardless of whether spent in or out of bed, as well as time in bed trying to resume sleep after the final awakening. This conceptualization *excludes* from the denominator time in bed engaged in non-sleep related activity before initiating an attempt to sleep and time in bed after finally waking and ceasing further attempts to sleep. We refer to this denominator as the duration of the sleep episode (DSE). DSE can be operationally defined as the sum of: sleep onset latency (SOL) + total sleep time (TST) + time awake after sleep onset but before final awakening (WASO) + time attempting to sleep after the final awakening (TASAFA). Sleep efficiency would therefore equal the ratio of TST / DSE (× 100). DSE components can be readily extracted from commonly used sleep diaries,[14] with the exception of TASAFA. An optional item in the "expanded consensus sleep diary (ECSD)"[14] measures TASAFA with the following question: "After your final awakening, how long did you spend in bed trying to sleep?" Thus, a precedent for the concept and measurement of TASAFA has been established in the literature.

USING TIB VERSUS DSE TO CALCULATE SE

An example of how TIB and DSE would be calculated using the same sleep diary entries illustrates the difference between the two variables. The example is based on hypothetical entries provided in the article describing the development of the Consensus Sleep Diary (CSD).[14] The hypothetical person "gets into bed" at 22:15, "tries to go to sleep" at 23:30, and falls asleep 55 minutes later. The person wakes up 3 times during the entire sleep episode for a total of 70 minutes awake. Note that the typical sleep diary does not ask whether the person was in or out of bed during periods of being awake in the middle of the sleep episode. However, neither TIB nor DSE requires that information to be calculated. The final awakening is recorded as 06:35, and the person stays in bed until 07:20 (45 minutes). As noted above, the core consensus sleep diary, like most sleep diaries, does not ask if the person was trying to sleep during the 45-minute time period between 6:35 to 7:20. But the ECSD does effectively measure the TASAFA component of DSE. The hypothetical person spent all 45 minutes trying to sleep after the final awakening.[14]

Based on these entries, TST equals 5 hours (300 minutes). TIB equals the difference between 22:15 and 07:20, for a total of 9 hours and 5 minutes (545 minutes). Using the conventional formula SE = TST / TIB, SE = 55%. Calculating DSE using the same hypothetical sleep diary data indicates that DSE = 55 minutes (SOL) + 300 minutes (TST) + 70 minutes (WASO) + 45 minutes (TASAFA), yielding a sum of 470 minutes. Using the proposed formula SE = TST / DSE, SE = 64%.

Two additional comments about these alternate formulas are worthy of mention. First, using TIB as the denominator will never yield SE levels that exceed those based on a DSE denominator. DSE and TIB will yield equal SE levels only when the bed is used exclusively for sleep; i.e., the person attempts to sleep immediately after entering the bed and gets out of bed immediately after the final awakening. To the extent that non-sleep related activities occur in bed, the DSE denominator will yield higher SE levels than those based on TIB. Second, the proposal to use DSE as the SE denominator is not meant to suggest that time in bed engaged in non-sleep related activity is unimportant. To the contrary, it directs attention to and facilitates distinguishing between non-sleep and sleep-related activities in bed. To that end, calculating the difference between TIB and DSE yields the amount of non-sleep related activity in bed, a variable with relevance to conditioning models of insomnia.[17] Using the hypothetical sleep diary data described above, TIB − DSE = 75 minutes, indicating that 75 minutes were spent in bed engaged in non-sleep related activity.

IMPLICATIONS FOR SLEEP RESEARCH AND PRACTICE

A commonly agreed upon conceptual and operational definition of SE that more accurately captures the construct of SE has several advantages. First, a consistently employed operational definition of SE should enhance communication and the interpretation of findings across multiple studies, a clear advantage especially for meta-analyses.[15]

Second, SE is frequently used as a primary outcome measure in insomnia research. Use of TIB as the SE denominator poses a methodological threat to outcome studies that employ SCT or SRT, central components of behavioral interventions for insomnia. The reason for the threat is as follows: Both SCT and SRT in large part aim to reduce (or eliminate) the amount of non-sleep related TIB, not as an end, but as a means of achieving the longer-term goal of insomnia reduction. Using SCT as an example, the hypothesized causal model would be: SCT Instructions → Reduction in Non-Sleep Related TIB → Insomnia Reduction. Reduction in non-sleep related TIB is, therefore, a mediator (or mechanism) by which SCT improves longer-term insomnia-related sleep outcomes. Improvement in the mediator is necessary but insufficient to conclude that SCT has its intended effect on insomnia. The problem with using TIB as the SE denominator is that SE will improve even if only TIB has been reduced. Mere compliance with the SCT instructions (an effect of treatment on the mediator) will, by definition, lead to improved SE even if there is absolutely no increase in the total amount of sleep. Therefore, use of TIB in the denominator makes it impossible to rely on SE to infer that SCT treatment altered the core symptoms of insomnia. This potential problem can be illustrated using actigraphic data from a randomized controlled trial comparing the effect of combined SCT and SRT (SCT + SRT) to a waiting-list control (WLC) group.[16] Posttest data showed that, as expected, TIB for the SCT + SRT group was 33 minutes less than in the WLC group. The lower TIB demonstrates that the SCT + SRT group complied with the intervention instructions, and thus shows that treatment had its intended effect on the mediator. Also as expected, SE at posttest (using the formula TST / TIB) was significantly higher in the treated group. At first glance, the higher SE might suggest that SCT + SRT had a positive effect on sleep itself. But the between group difference in TST was not significant, and the SCT + SRT group actually slept on average six minutes less than the WLC. Higher SE in the SCT + SRT group was entirely due to reduced TIB, not an increase in TST. These results demonstrate that, for interventions that restrict non-sleep-related time in bed, use of TIB in the denominator allows for the possibility that an increase in SE could be entirely due to complying with treatment instructions rather than the ultimate goal of insomnia reduction. Using DSE in the denominator eliminates this potential problem because SE will increase only if one or more core insomnia-related outcomes improve (TST, SOL, WASO, and TASAFA). In fact, this study[16] found that treatment produced significantly lower scores on both SOL and WASO (TASAFA could not be extracted from the reported data), indicating improvement in SE. Therefore, an advantage of using DSE as the SE denominator is that it eliminates concern that improvement in SE merely reflects effective implementation of SCT/SRT interventions rather than a change in core insomnia-related sleep outcomes. Third, measurement of SE has important implications for implementation of SRT. SRT involves systematically altering the duration of an individual's sleep schedule, usually based on SE benchmarks. Participants in SRT are instructed to continue reducing TIB when SE remains below a particular level, usually 85%. SE computed using TIB that includes non-sleep related activity will yield underestimates of actual SE (because of the inflated denominator in the computation). Using an underestimate of actual SE in applying SRT will lead to unwarranted reductions in time allotted for sleep. Similarly, SRT instructions also typically advise participants to hold their sleep schedule steady between 85% and 89% SE. If SE reaches 90%, and the participant does not feel sufficiently rested, time should be added to the sleep schedule. Using an underestimate of actual SE could again lead to problems. In this scenario, the most obvious potential difficulty would be that participants do not move ahead with the process of adding time back into their sleep schedules when, in fact, they ought to be doing so. Such instances could create an unnecessary degree and duration of sleep deprivation, which is likely to adversely affect well-being and potentially result in poorer treatment outcomes. Possible problems associated with SRT-induced sleep deprivation include decreased vigilance, slowed reactions, and impaired performance.[18] Underestimates of SE in SRT are, therefore, likely to result in a lag or a delay in progressing through the process of SRT. A more accurate measure of SE in SE benchmark guided SRT could lead to better outcomes and lower dropout rates.

Finally, the concept of DSE underscores the potential value in differentiating between sleep and non-sleep related TIB, both before the initial attempt to sleep and after the final awakening. Further scrutiny of the role that each of these variables play in the development, maintenance or exacerbation of insomnia may prove fruitful.

In summary, operational definitions of SE have been inconsistent and often do not accurately reflect the SE construct. These discrepancies are likely to hamper the interpretation and synthesis of research findings. Imprecise measurement of SE may also adversely affect behavioral clinical interventions and insomnia outcome research. The primary source of the problem is the denominator commonly used in the formula for SE: ratio of total sleep time (TST) / time in bed (TIB) (multiplied by 100 to yield a percentage). When taken literally, TIB produces a distorted measure of SE because it can include time in bed engaged in non-sleep related activities such as reading, watching television, or simply lying in bed thinking about the upcoming day. DSE, the time span that begins when the person engages in behaviors intended to induce sleep and ends when the person finally wakes and no longer attempts to sleep, is offered as a denominator that will yield a more precise and more valid operationalization of the SE construct. An alternate formula for SE is thus proposed: SE = TST / DSE (× 100) where DSE = SOL + TST + WASO + TASAFA. DSE can be easily calculated using standard sleep diary entries and one item from the Expanded Consensus Sleep Diary.[14] This conceptualization

and proposed measure of SE has implications for insomnia research and practice. Future research should examine if use of DSE in the calculation of SE has a positive impact on the understanding and treatment of insomnia. If not, perhaps other, better ways to measure SE will emerge from these efforts.

ABBREVIATIONS

DSE, duration of the sleep episode
SCT, stimulus control therapy
SE, sleep efficiency
SOL, sleep onset latency
SRT, sleep restriction therapy
TASAFA, time attempting to sleep after the final awakening
TIB, time in bed
TST, total sleep time
WASO, time awake after initial sleep onset but before final awakening

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