

Hours slept, not hours worked: predictors of next-day recovery in emergency physicians

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Abstract

Emergency physicians (EPs) continuously staff emergency departments, where rotating schedules, extended shifts, and night work may limit sleep opportunities and hinder recovery. This 4-week repeated-measures field study examined associations among daily sleep duration, shift characteristics, and next-day self-reported recovery across 447 working-day observations from 44 EPs. Recovery was higher on days when physicians slept longer than their average sleep duration, whereas neither shift duration relative to physician's average nor the sleep-by-shift-duration interaction was significantly associated with recovery. With respect to shift type, night shifts were associated with lower sleep duration and lower recovery than afternoon and morning shifts. Physician-level bootstrap mediation analyses indicated that sleep duration accounted for part of the association between shift type and recovery, while significant direct associations remained for morning and afternoon shifts relative to night shifts. These findings identify protected sleep opportunity and circadian-informed scheduling as potentially modifiable targets for supporting EP recovery and well-being.

1 Introduction

Emergency departments (EDs) are continuously operating, hospital-based clinical settings that provide unscheduled care to individuals requiring immediate medical attention¹. Within these complex sociotechnical environments, emergency physicians (EPs) manage responsibilities ranging from acute patient stabilization to administrative duties while contending with high workloads, time pressure, and substantial environmental unpredictability^{2,3}. These demands are sustained not for a single shift but across a rotating schedule, so the question of how physicians recover between duty periods is as consequential as how they perform within them

Around-the-clock ED operation is sustained through shift work, a structural feature of emergency medicine in which physicians rotate through morning, afternoon, and overnight shifts of 8 to 12 hours to maintain continuity of care^{2,4,5}. Shift work is conventionally defined as scheduled work occurring outside the hours of 7:00 a.m. to 6:00 p.m. and is especially prevalent in emergency medicine^{6,7}. The physiological cost of such schedules is best understood through the two-process model of sleep–wake regulation, in which sleep timing and quality are governed by the interaction between a homeostatic process that accumulates sleep pressure during wakefulness and a circadian process that sets the biological timing of sleep propensity and alertness⁸. Rotating and night-shift schedules require wakefulness during the circadian window of maximal sleep propensity and sleep during the circadian window of heightened alertness, thereby placing the two processes in conflict and producing circadian misalignment^{9,10}. Night-shift work in particular compels wakefulness throughout the habitual sleep period and displaces sleep to biologically atypical times, so that daytime sleep opportunities are both curtailed and occur at an adverse circadian phase¹⁰. Sleep obtained against the circadian rise in alertness is characteristically shorter, more fragmented, and terminated earlier than sleep taken at the habitual phase, so that the homeostatic pressure accumulated across an extended waking period is only

partially discharged before the next duty period begins. As a result, the homeostatic sleep pressure accumulated across a long waking day may not be fully relieved. Repeated transitions between shift types further compound this misalignment by requiring ongoing readjustment of the sleep–wake cycle, promoting insufficient sleep duration and cumulative sleep loss^{9,11}.

Beyond their timing, shifts also vary in duration, which constitutes a second and partly independent pathway to impaired recovery. A longer shift increases time on task and prolongs continuous wakefulness, allowing homeostatic sleep pressure and task-related fatigue to accumulate further before the shift ends⁶. It simultaneously compresses the interval remaining before the next duty period, narrowing the window available for sleep and off-work recovery through which accumulated pressure is normally discharged^{12,13}. Consistent with this, longer working hours have been linked to greater fatigue, burnout, and an elevated risk of errors among healthcare workers^{14–16}. Shift duration and shift timing, therefore, represent distinct pathways to impaired recovery: the first operating through accumulated homeostatic load and a compressed inter-shift interval, the second through the circadian phase at which the subsequent sleep episode is taken. Whether these pathways also interact, such that the recovery cost of extended hours is greatest when sleep is already curtailed, is less well established.

The consequences of shift timing and duration are realized through their effect on recovery. Recovery refers to the set of restorative processes and behaviors through which strain accrued during work is reversed and psychophysiological systems return to pre-stressor levels^{13,18}. Under effort–recovery models, the strain generated by a work period is not, in itself, pathological, provided the subsequent off-work interval affords sufficient opportunity for these processes to complete; it is the repeated failure to recover, rather than the strain itself, that accumulates to impair health and well-being¹². Recovery is therefore determined jointly by how much strain a work period generates and by how much unencumbered off-work time follows it, the two quantities that shift duration and shift timing respectively govern.

Sleep is a principal mechanism of physiological downregulation and restoration and is thought to protect against impaired well-being^{12,17}. When sleep is insufficient or of poor quality, the homeostatic recovery that normally occurs during sleep is constrained, limiting opportunities for restoration, promoting fatigue, and elevating the risk of adverse health outcomes^{13,18}. Sleep duration may therefore represent a proximal pathway linking shift characteristics to recovery. It captures the amount of sleep actually obtained rather than the sleep opportunity nominally afforded by the roster. However, lack of sleep can lead to impaired well-being and increase in fatigue.

Fatigue is defined as a state of discomfort characterized by exhaustion or tiredness of sufficient severity to impair normal functioning¹⁹. Among EPs, fatigue is associated with outcomes that are consequential for both human performance and patient safety, including reduced work performance and impaired cognitive functioning². Sustained over time, fatigue may contribute to physiological strain, diminished occupational well-being, and burnout^{20,21}. From a patient-safety perspective, fatigue has been identified

as a contributor to medical errors, including diagnostic and management errors, medication errors, delayed diagnoses, and impaired clinical judgment^{22,23,24}. Burnout has also been associated with lower job satisfaction and intentions to quit emergency medicine among EPs³. These downstream consequences are what make the antecedent question worth examining directly: how much sleep physicians actually obtain, and what determines it.

A growing body of evidence links insufficient and poor-quality sleep to impaired physician well-being across healthcare settings and countries. Inadequate sleep duration has been consistently linked to poorer mental health outcomes. Among 232 Japanese physicians, sleeping fewer than 6 hours per day was associated with higher odds of experiencing high stress and depressive symptoms, irrespective of working hours¹⁴. Similarly, among 300 Peruvian healthcare professionals, sleeping fewer than 7 hours per night was independently associated with burnout²⁵. Sleep also appears to interact with work demands in shaping well-being outcomes. In a study of 2,081 Taiwanese healthcare workers, sleep duration partially mediated the nonlinear relationship between weekly working hours and burnout¹⁵, a finding that directly motivates the present study's focus on sleep as a physiological buffer. Quality appears to matter alongside quantity: among Portuguese healthcare professionals, poorer sleep quality and lower sleep health were associated with greater fatigue and perceived cognitive difficulties, with shift workers sleeping more poorly than those on regular schedules²⁶.

Within emergency medicine specifically, these links between sleep and fatigue recur. Sleep duration is a strong predictor of fatigue in this population: across 360 emergency medicine residents in a nationwide study in Türkiye, each additional hour of daily sleep was associated with a 41% reduction in fatigue²⁷. The same pattern extends to cognitive function. Among 13 attending EPs working rotating day and overnight shifts, short-term memory declined following both shift types. Poor sleep quality was reported for 30.7% of observations, and severe mental and physical fatigue for 38.4%⁵. This burden is also patterned by shift timing: objective monitoring of 17 EPs across 392 shifts showed that night shifts carried greater fatigue risk, with physicians spending 23.52% of on-shift time in a fatigue-risk state linked to impaired performance⁶.

Collectively, prior work indicates that sleep duration, working hours, and shift timing are associated with fatigue, recovery, cognitive functioning, burnout, and physician well-being. However, this evidence is almost entirely cross-sectional or between-person. It establishes that physicians who sleep less report worse outcomes, but not whether a given physician recovers less following their own shorter-sleep days. Because sleep duration, shift type, and recovery all vary substantially from day to day within the same individual, between-person comparisons cannot separate the consequences of working a night shift from the characteristics of physicians who work more of them. What remains largely absent is a daily diary design in which repeated within-person observations are linked to administrative shift records, allowing shift type, shift duration, sleep, and next-day recovery to be ordered in time for the same physician. This gap is critical as night shifts may curtail sleep through circadian misalignment, longer

shifts may compress the time available for recovery, and sleep is an established substrate for physiological and psychological restoration^{2,6,13}.

The present study addresses this gap by examining the associations of daily sleep duration and shift-related work characteristics with next-day recovery among EPs. The shift characteristics we consider are shift duration and shift type. We examine the joint association between daily sleep duration and shift duration and next-day recovery, with sleep duration serving as a moderator, focusing on whether adequate sleep offsets the cost of extended hours. We also examine whether recovery differs by shift type after accounting for daily sleep duration, and whether daily sleep duration mediates the association between shift type and recovery. Sleep duration here acts as a mediator: since shift timing is fixed by the roster before the sleep episode occurs, it can plausibly influence recovery through the sleep it permits. All associations are estimated within physicians, so that each physician serves as their own comparison. Specifically, we address four research questions:

- 1. How are daily sleep duration and daily shift duration jointly associated with recovery among EPs?
- 2. How is shift type associated with daily sleep duration?
- 3. How is shift type associated with recovery before and after accounting for daily sleep duration, as a precondition for mediation?
- 4. Does daily sleep duration mediate the association between shift type and recovery?

2 Results

Analyses were based on 447 working-day observations from 44 EPs. Of these, 169 followed morning shifts, 202 followed afternoon shifts, and 76 followed night shifts, contributed by 42, 42, and 32 physicians, respectively. Mean recovery across all observations was 57.18% (out of 100%; SD = 22.81), and mean sleep duration was 7.24 hours (SD = 1.74). Descriptive statistics for all study variables, overall and by shift type, are presented in Table 1 as Mean (SD). Because the night category comprised 76 observations from 32 physicians, the night contrasts are the least precisely estimated in the analyses that follow. No correction for multiple comparisons was applied, and the three shift-type contrasts are interpreted jointly rather than as independent tests. Significance level was set at a threshold of 5%

Table 1
Descriptive statistics for all study variables by shift type

Variable	Overall	Morning	Afternoon	Night
Recovery (%)	57.18 (22.81)	62.96 (20.60)	56.88 (21.92)	45.13 (25.17)
Sleep duration (hours)	7.24 (1.74)	8.16 (1.38)	6.98 (1.51)	5.91 (1.94)
Proportion of nighttime sleep (%)	64.91 (33.52)	88.74 (9.73)	69.10 (18.77)	0.77 (5.41)
Shift duration (hours)	8.64 (0.67)	8.60 (0.54)	8.44 (0.71)	9.25 (0.49)
Consecutive workday (days)	1.91 (1.08)	1.54 (0.76)	1.93 (1.06)	2.70 (1.36)

2.1 Sleep duration and shift duration

Recovery was higher on days when physicians slept longer than their average sleep duration, but there was insufficient evidence that recovery was independently associated with working a shift longer than the physician's average shift duration or that shift duration modified the sleep-recovery association. At a physician's average shift duration, each additional hour of sleep relative to that physician's average sleep duration was associated with a 4.22-percentage-point higher recovery score within physicians after adjustment for shift type, between-physician differences in average shift duration and average sleep duration, and consecutive workday (95% CI 3.15 to 5.30, $p < .001$). At a physician's average sleep duration, each additional hour of shift duration relative to that physician's average shift duration was associated with 1.82 percentage points lower recovery within the same physician, although this association was not statistically significant ($\beta = -1.82$, 95% CI -4.48 to 0.84 , $p = .179$). The sleep-by-shift-duration interaction was negative but not statistically significant ($\beta = -1.44$, 95% CI -3.12 to 0.24 , $p = .093$). There was therefore insufficient evidence that the within-physician association between sleep duration and recovery changed with increasing shift duration, although the direction of the estimate suggested that the positive sleep-recovery association may be weaker when physicians worked shifts longer than their average shift duration. The model accounted for 19.5% of the variance in recovery through its fixed effects (marginal $R^2 = 0.195$) and 59.3% of the variance, including physician-specific random intercepts (conditional $R^2 = 0.593$). Adding the sleep-by-shift-duration interaction explained an additional 0.2% of the variance in recovery ($\Delta R^2_{\text{marginal}} = .002$, Cohen's $f^2 = .002$). Fitted slopes across within-physician values of shift duration are shown in Fig. 1. This model was estimated using 447 observations from 44 physicians.

2.2 Sleep and shift type

2.2.1 Shift type and sleep duration

Sleep duration varied systematically by shift type, with night shifts associated with the shortest sleep duration. Relative to night shifts, afternoon shifts were associated with 1.06 additional hours of sleep within physicians (95% CI 0.59 to 1.52, $p < .001$), while morning shifts were associated with 2.25 additional hours (95% CI 1.78 to 2.73, $p < .001$), after accounting for shift duration and consecutive workday. Morning shifts were also associated with 1.20 additional hours of sleep compared with afternoon shifts (95% CI 0.89 to 1.51, $p < .001$). Relative to a mean sleep duration of 7.24 hours, the morning versus night difference represents approximately a 31.1% difference in nightly sleep within the same physician. Marginal and conditional R^2 were 0.212 (21.2%) and 0.348 (34.8%). This model was estimated on 447 observations from 44 physicians.

2.2.2 Shift type and recovery, before and after accounting for sleep duration

Recovery was highest following morning shifts, intermediate following afternoon shifts, and lowest following night shifts; these differences diminished once sleep duration was considered.

Before sleep duration was included, recovery was 11.88 percentage points higher following afternoon shifts than night shifts (95% CI 6.52 to 17.23, $p < .001$) and 19.57 percentage points higher following morning shifts (95% CI 14.11 to 25.02, $p < .001$), after adjustment for shift duration and consecutive workday. Recovery was also 7.69 percentage points higher following morning than afternoon shifts (95% CI 4.13 to 11.25, $p < .001$). Given that recovery was recorded in 10-percentage-point increments and had a standard deviation of 22.81 points, the morning-versus-night difference of 19.57 points corresponds to approximately two slider steps and 0.86 standard deviations.

After sleep duration was included, these associations attenuated. Relative to night shifts, recovery remained higher following afternoon shifts by 7.78 percentage points (95% CI 2.64 to 12.93, $p = .003$) and following morning shifts by 10.74 percentage points (95% CI 5.11 to 16.38, $p < .001$). The morning-versus-afternoon contrast was reduced to 2.96 percentage points and was no longer statistically significant (95% CI, - 0.60 to 6.51; $p = .103$). Among physicians, each additional hour of sleep relative to a physician's usual sleep duration was associated with a 3.96-percentage-point higher recovery score (95% CI, 2.90 to 5.02; $p < .001$). Marginal and conditional R^2 were 0.132 (13.2%) and 0.510 (51.0%) for the model excluding sleep duration and 0.198 (19.8%) and 0.571 (57.1%) for the model including it. Both models were estimated on 447 observations from 44 physicians.

Three conditions for mediation were therefore met: shift type was associated with sleep duration, sleep duration was positively associated with recovery among physicians, and the shift-type coefficients attenuated once sleep duration was entered into the model. Sleep duration was accordingly evaluated formally as a potential mediator.

2.2.3 Mediation analysis

Indirect associations between shift type and recovery through sleep duration were statistically significant for all three shift-type contrasts and were largest for the morning versus night comparison. Direct associations remained statistically significant for afternoon versus night and for morning versus night shifts, whereas the direct morning versus afternoon association was not. Estimates are presented in Table 2. All values are recovery percentage points. Confidence intervals are percentile bootstrap intervals from 5,000 physician-level cluster resamples, of which 4,961 (99.2%) converged. Models adjusted for shift hours worked, and consecutive workday, with shift type and sleep duration decomposed into within- and between-physician components. $N = 447$ observations from 44 physicians.

Table 2
Indirect, direct, and total within-physician associations between shift type and recovery, with sleep duration as mediator

Contrast	Indirect (95% CI)	Direct (95% CI)	Total (95% CI)
Afternoon vs night	4.20 (1.73, 7.43)	7.69 (1.02, 14.19)	11.89 (4.71, 18.99)
Morning vs night	8.95 (5.32, 13.45)	10.46 (3.67, 16.81)	19.42 (13.09, 26.15)
Morning vs afternoon	4.75 (2.88, 7.15)	2.78 (– 0.43, 5.69)	7.53 (4.59, 10.37)

In this analysis, indirect associations were calculated within each bootstrap resample as the product of the within-physician *a* and *b* paths. Direct associations were obtained from the sleep-adjusted recovery model, and model-implied total associations were calculated as the sum of the direct and indirect associations. The direct associations correspond conceptually to the sleep-adjusted shift-type coefficients reported in § 2.2.2, although the numerical values may differ slightly because Table 2 reports the mean of the bootstrap distribution, whereas § 2.2.2 reports coefficients estimated from the original analytic sample. The estimated within-physician mediation pathways are summarized in Fig. 2, illustrating the association of shift type with sleep duration (*a* path), the association of sleep duration with recovery (*b* path), and the direct and model-implied total associations of shift type with recovery (*c'* and *c* paths, respectively).

Overall, the findings were consistent with sleep duration accounting for part of the observed association between shift type and recovery. The indirect pathway through sleep duration corresponded to approximately 35%, 46%, and 63% of the afternoon-versus-night, morning-versus-night, and morning-versus-afternoon differences, respectively. The morning-versus-afternoon difference was substantially attenuated after accounting for the indirect pathway via sleep duration.

2.2.4 Sensitivity analysis

The estimated indirect associations attenuated progressively as the assumed positive residual mediator–outcome correlation increased, reaching zero at $\rho = 0.346$. At that value, the adjusted sleep-to-recovery association, and consequently all three indirect associations, were reduced to zero. An unmeasured within-physician factor that induces a residual sleep–recovery correlation of approximately 0.35 would therefore be sufficient to eliminate the estimated indirect associations after accounting for the modeled multilevel structure and covariates.

Values at $\rho = 0$ are derived analytically from the point estimates of the mediator and outcome models and differ marginally from the bootstrap medians in Table 2, which are computed across resamples. Sensitivity results are presented in Table 3 and Fig. 3.

Table 3

Sensitivity of Estimated Indirect Associations to Assumed Residual Mediator–Outcome Correlation

ρ	Sleep-to-recovery coefficient	Afternoon vs night	Morning vs night	Morning vs afternoon
-0.80	18.29	19.34	41.21	21.86
-0.40	8.65	9.15	19.49	10.34
0.00	3.96	4.19	8.92	4.73
0.10	2.88	3.04	6.48	3.44
0.20	1.76	1.87	3.97	2.11
0.346	0.00	0.00	0.00	0.00
0.40	-0.73	-0.78	-1.65	-0.88
0.80	-10.38	-10.97	-23.37	-12.40

3 Discussion

This 4-week field study examined how daily sleep duration and shift characteristics relate to next-day recovery among EPs, and whether sleep duration helps account for differences in recovery across shift types. Because sleep duration, shift characteristics, and recovery all varied across working days within the same physician, analyses were conducted at the working-day observation level, with each physician serving as their own comparison. Three findings emerged: recovery was higher on days when physicians slept longer than their average sleep duration, sleep duration varied systematically by shift type, and sleep duration accounted for part but not all of the recovery difference across shift types.

Recovery was higher on days when physicians slept longer than their average sleep duration, whereas working a shift longer than the physician's average shift duration was not independently associated with recovery. The sleep-by-shift-duration interaction was also not statistically significant, indicating insufficient evidence that the recovery benefit associated with additional sleep varied according to the duration of the preceding shift. The interaction estimate was in the anticipated direction, with a weaker sleep–recovery association as shift duration increased, but the confidence interval included zero, and the finding should not be interpreted as evidence of moderation or buffering. Two explanations are plausible. Sleep duration and shift duration may exert largely independent effects on recovery, in which case an additive model may provide the more appropriate representation. Alternatively, the study may not have had sufficient power to detect a modest interaction in a sample of 447 observations, particularly because most shift durations were concentrated between 8 and 10 hours. The positive within-physician association between sleep duration and recovery is consistent with the homeostatic component of the two-process model, whereby sleep reduces accumulated sleep pressure. When sleep is shortened relative to a physician's average duration, recovery may remain incomplete, and the following working day may begin with greater residual fatigue. These findings are consistent with

evidence linking shorter sleep to poorer physician well-being, including stress and depressive symptoms^{14,25}, and extend that literature by connecting daily sleep, shift duration, and next-day recovery within the same individuals rather than across them.

Sleep duration differed substantially by shift type, forming a graded pattern in which night shifts were followed by the shortest sleep, afternoon shifts by intermediate sleep, and morning shifts by the longest. This gradient is consistent with the circadian component of sleep and wake regulation. Night-shift work displaces the main sleep episode into the daytime, when the circadian pacemaker is actively promoting wakefulness; sleep initiated against this wake-promoting signal is characteristically shorter, more fragmented, and terminated prematurely, largely independent of how much homeostatic sleep pressure has accumulated^{6,9,10,28}. Night shifts therefore impose a dual penalty. They compress the available sleep opportunity, and they require that whatever sleep is obtained be taken at an adverse circadian phase, degrading both the duration and the restorative quality of sleep. Two observations support this reading. Sleep following night shifts was more variable than sleep following morning shifts (Table 1), consistent with the difficulty of achieving consolidated daytime sleep and with individual differences in tolerance to circadian misalignment. In addition, the proportion of sleep obtained during nighttime (10 pm to 6 am) was substantially lower following night shifts (Table 1), which provides a direct, if descriptive, indication that the sleep obtained after night work was displaced in phase and not merely shortened in duration.

Shift type was also associated with next-day recovery, with recovery, highest following morning shifts, intermediate following afternoon shifts, and lowest following night shifts. These differences attenuated once sleep duration was considered, most markedly for the morning versus afternoon comparison, which was no longer statistically significant. The mediation findings were consistent with sleep duration accounting for part of the association between shift type and recovery: indirect associations were statistically significant for all three contrasts, while direct associations remained for afternoon versus night and morning versus night shifts. The pattern differs meaningfully across contrasts. For the two daytime shift types, differences in sleep duration appear to account for most of the recovery difference, which is what would be expected if morning and afternoon shifts differ mainly in how much sleep they permit rather than in the circadian phase at which that sleep is taken. For the night contrasts, a substantial direct association persisted, indicating that the recovery cost of night work is not reducible to lost sleep alone. Other features of night work may contribute, including the circadian phase of the sleep obtained, reduced sleep quality independent of duration, working during the biological night itself, and disruption to social and domestic routines¹⁰. This is consistent with objective monitoring work showing elevated fatigue risk during later and night shifts that is not fully explained by prior sleep duration⁶.

The sensitivity analysis qualifies these mediation findings. The estimated indirect associations attenuated as the assumed residual mediator and outcome correlation increased and reached zero at $\rho = 0.346$. An unmeasured within-physician factor associated with both sleep and recovery at a correlation of roughly 0.35 would therefore be sufficient to eliminate the estimated indirect pathway entirely. This is not a large correlation, and candidate factors are readily identifiable: daily workload, patient acuity, acute stress, illness, family demands, and sleep quality would each plausibly reach that magnitude, and none

was measured here. The mediation results should accordingly be read as consistent with a sleep pathway rather than as establishing one.

Several considerations bound the interpretation of these findings, beginning with measurement. Recovery was assessed with a single, self-developed bipolar item that treated exhaustion and recovery as opposite poles of one continuum. Because exhaustion and recovery may be related but distinct constructs, this approach may have constrained construct validity, and future work would benefit from multi-item or validated recovery measures. Sleep duration was derived from self-report rather than actigraphy or polysomnography, so it captures perceived time asleep rather than sleep architecture or circadian phase directly. A more specific concern arises from the wording of the sleep items, which were adapted from the Pittsburgh Sleep Quality Index and asked what time participants went to sleep "LAST NIGHT" and woke "TODAY". This phrasing has a documented failure mode among shift workers, whose principal sleep episode may occur during the day and may not correspond to what a respondent understands as "last night". Two physicians showed systematic inversion or temporal misanchoring across nearly all of their records and were excluded, and screening rules were applied to identify implausible shift and sleep overlaps in the remaining data. Residual misreporting cannot be excluded, and because this failure mode is most likely following night shifts, it has the potential to bias the shift-type comparisons that are central to this paper. Shift duration was derived from administrative rosters rather than hours actually worked, and participant notes indicated that physicians sometimes departed before the rostered end time. The continuous shift-duration measure may therefore contain measurement error. Finally, daily surveys could be completed after the distribution time, introducing variable recall intervals that may differ systematically by shift type.

Design and sampling considerations further bound interpretation. The analytic sample comprised 447 working-day observations from 44 physicians within a single hospital system, which may limit generalizability to other ED settings and scheduling cultures. Night shifts contributed 76 of these observations from 32 physicians, so the night contrasts, which carry much of the paper's argument, are the least precisely estimated. Sleep duration served as a moderator in the shift-duration analysis and as a mediator in the shift-type analysis; although this reflects a genuine difference in the causal position of the two exposures, it means the two sets of findings rest on different identifying assumptions and should not be read as a single unified model. No adjustment was made for multiple comparisons. Finally, given the observational design, the estimated associations should not be interpreted as causal effects. The temporal ordering imposed in the analysis, in which the shift precedes the sleep episode, which in turn precedes next-day recovery, is consistent with a causal sequence but does not establish one.

These limitations, notwithstanding, the pattern of findings points toward concrete, mechanism-aligned levers for protecting physician recovery. Two independent associations emerged, each with a distinct implication. Additional sleep relative to a physician's average sleep duration was associated with higher recovery, supporting scheduling practices that protect sleep opportunity, including inter-shift intervals long enough to accommodate a full sleep episode and avoidance of rosters that combine longer shifts with night work. Although the estimated association between working a shift longer than the physician's

average shift duration and recovery was negative, it was not statistically significant, and the sleep-by-shift-duration interaction also did not reach statistical significance. The findings therefore do not support the conclusion that longer shifts independently reduce recovery or that additional sleep reliably buffers their effects. Because these associations were additive rather than interactive in this sample, neither measure should be treated as a substitute for the other. Since sleep duration also accounted for only part of the night-shift penalty, duration-focused measures should be complemented by strategies addressing circadian misalignment directly, such as forward-rotating schedules²⁹, managed light exposure, and strategic napping such as napping after the shift. Fatigue-management education and sleep-hygiene resources may help physicians convert protected time into actual sleep, but these findings suggest such measures are best positioned as adjuncts to structural scheduling changes rather than as substitutes for them.

Future work should address the measurement limitations identified here. Objective, wearable-derived sleep and circadian metrics would allow the phase-related component of the night-shift penalty to be separated from the duration-related component, which the present design can only infer. Measuring daily workload and patient acuity would address the most plausible sources of the residual confounding that the sensitivity analysis identified as sufficient to eliminate the mediation pathway. Coupling these with validated indices of recovery, well-being, and burnout would allow the mechanisms proposed here to be tested directly, and would move the field from association toward actionable, individually tailored countermeasures for the physicians who staff the ED around the clock.

4 Methods

4.1 Participants

Emergency physicians were recruited from a major hospital system in South Carolina, USA as part of a larger survey-based investigation. Forty-six physicians enrolled in the study, of whom 45 completed the baseline survey. Among those completing the baseline survey, 28 were women and 17 were men. Participants ranged in age from 30 to 65 years, and years of emergency medicine practice ranged from less than 1 year to 36 years. The final analytic sample comprised 44 of these physicians, following the exclusions described in Section 4.4.

4.2 Ethics approval and consent

All study procedures involving human participants were reviewed and approved by the Prisma Health IRB under protocol 2148726-1. The study was conducted in accordance with the Declaration of Helsinki and its later amendments. All participants provided consent prior to enrollment, including consent for the use of administrative shift records.

4.3 Study design

The study used a 4-week repeated-measures design and was conducted in April 2024. Participants completed a baseline survey, repeated daily surveys, and weekly surveys throughout the study period.

The baseline survey collected demographic and professional characteristics. Daily surveys assessed sleep and self-reported recovery, whereas administrative records provided scheduled shift start and end times. Weekly survey data were collected as part of the larger investigation and were not used in the present analyses.

Daily surveys were administered through Qualtrics and distributed by text message around noon (~12:00 p.m.). Each survey was assigned to a designated study date. Participants could complete a survey after the distribution time, and responses were accepted for up to 48 hours following distribution. Participants received gift cards in proportion to the number of surveys completed.

Administrative shift records and daily survey responses were aligned according to the designated survey date. For a survey assigned to day t , the indexed shift was the shift with a start date on the preceding calendar day, $t - 1$. For example, the recovery reported for April 2 was linked to the shift that began on April 1. The reported sleep episode occurred after the indexed shift and before recovery on the designated survey day. Accordingly, the observation-level temporal sequence was the shift beginning on day $t - 1$, the subsequent sleep episode, and recovery on day t . For shifts crossing midnight, complete administrative start and end datetimes were retained to characterize shift timing and duration accurately, while linkage to the survey observation was based on the shift start date. A schematic representation of this temporal alignment is provided in Fig. 4.

4.3.1 Variables of interest

The following variables were selected from the larger survey and administrative datasets.

- a) Recovery Percentage: The primary outcome was self-reported recovery percentage. In each daily survey, participants were asked, “Think about your state of exhaustion/recovery TODAY, ranging from being ‘extremely exhausted/0% recovered’ to ‘not at all exhausted/100% recovered.’” Responses were recorded using a slider ranging from 0% to 100% in 10-percentage-point increments. The measure represented participants' perceived recovery state on the designated survey day. A single-item measure was used to reduce participant burden associated with repeated daily assessments, consistent with prior research supporting single-item measures in intensive longitudinal studies³⁰.
- b) Sleep duration: Sleep-related variables were assessed in the daily surveys using items adapted from the Pittsburgh Sleep Quality Index (PSQI). Participants reported sleep time in response to the item, “What time did you go to sleep LAST NIGHT?” and wake time in response to the item, “What time did you wake up TODAY?” Sleep and wake times were reported in 15-minute intervals from 12:00 a.m. to 11:45 p.m. and coded from 1 to 96. Daily sleep duration was calculated as the elapsed time between sleep onset and wake time. When the wake-time code preceded the sleep-onset code, 96 code units, equivalent to 24 hours, were added to the wake-time to account for sleep crossing midnight.
- c) Proportion of nighttime sleep: For each observation, the proportion of the reported sleep episode falling between 22:00 and 06:00 was calculated as a descriptive index of the circadian placement of

sleep. This variable was not used in the inferential models and is reported descriptively in Table 1.

d) Shift times: Shift start and end times were obtained from administrative shift records. The administrative data included *datetime_start* and *datetime_end* variables, which captured the start and end times of each shift, respectively. Shift timing was also recorded in 24-hour time using the *StartTime24hr* and *EndTime24hr* variables and reformatted into *start_time* and *end_time* variables (e.g., 06:00 and 15:00). These variables were used to characterize the timing, duration, and type of each scheduled shift. The term "shift duration" is used throughout for this variable in both forms.

e) Shift type: Each shift was classified according to the time-of-day period containing the greatest proportion of its scheduled hours. Morning was defined as 06:00 to 13:59, afternoon as 14:00 to 21:59, and night as 22:00 to 05:59. For each shift, the number of scheduled hours occurring within each time-of-day period was calculated, and the shift was assigned to the period containing the greatest proportion of its scheduled duration. Four observations resulted in ties between morning and afternoon; these were assigned to morning on the basis of start time.

f) Consecutive workday: Consecutive workdays were derived from each physician's sequence of worked calendar days. The first day in a consecutive work sequence was coded as 1, incrementing by one for each subsequent consecutive working day and resetting to 1 following a non-working day. Consecutive workday was entered as a continuous linear term in all models as a covariate.

4.4 Data preprocessing

The initial daily survey dataset comprised 1,288 observations from 46 physicians. Variables related to sleep, scheduled shifts, and recovery were selected from the survey and administrative datasets. Observations with missing recovery percentage were excluded first ($n = 125$), followed by observations with missing sleep-duration data ($n = 67$), leaving 1,096 observations eligible for linkage with administrative shift records. Shift duration was calculated as the elapsed time between *datetime_start* and *datetime_end*, expressed in hours. Administrative shift records were then linked to daily survey observations using the predefined temporal-alignment procedure. For each survey date, the linked shift was the shift worked on the preceding calendar day, the reported sleep episode occurred after that shift, and the recovery score reflected perceived recovery on the subsequent survey day. Observations without a scheduled shift on the preceding calendar day were excluded ($n = 622$), leaving 474 working-day observations from 46 physicians. Two additional data-quality rules were applied to identify records in which reported sleep timing was inconsistent with the scheduled shift. First, observations were flagged when the reported sleep period overlapped the scheduled shift by at least 1 hour. Second, observations were flagged when reported sleep onset occurred between 06:00 and 16:00 following a morning shift, which was inconsistent with the temporal sequence assumed in the study design. Together, these rules removed 27 observations, leaving 447 observations from 44 physicians. The flow of observations from the initial survey dataset to the final analytic dataset is shown in Fig. 5.

4.5 Statistical analysis

Analyses were conducted at the working-day level to capture day-to-day variation in sleep, shift characteristics, and recovery within physicians. Unconditional random-intercept models yielded intraclass correlation coefficients of 0.36 for recovery and 0.11 for sleep duration, indicating that approximately 36% and 11% of the total variance, respectively, was attributable to between-physician differences. These values supported the use of linear mixed-effects models with physician-specific random intercepts to account for the non-independence of repeated working-day observations.

Continuous exposures were decomposed into within- and between-physician components when the research question required separation of day-to-day within-physician variation from between-physician differences. The within-physician component represented each observation's deviation from that physician's mean, and the between-physician component represented the physician-specific mean centered at the sample mean. Sleep duration and shift duration were decomposed in the sleep-by-shift-duration model. Shift type and sleep duration were decomposed in the shift-type and mediation models, while shift duration was included in those models as a continuous adjustment covariate.

Models were estimated by restricted maximum likelihood, except where models differing in fixed-effects structure were compared, in which case both were refitted by maximum likelihood. All models specified physician-specific random intercepts only. Random slopes for within-physician sleep duration were not tested. Statistical inference for fixed effects was based on Wald z tests, as implemented in statsmodels, rather than on Satterthwaite or Kenward-Roger degrees of freedom; with 44 clusters this may yield slightly anti-conservative p values for fixed effects. All statistical tests were two-sided. Effect estimates are reported with 95% confidence intervals and exact p values, except where $p < .001$. No adjustment was made for multiple comparisons.

Model fit is reported using marginal and conditional R^2 following Nakagawa and Schielzeth, representing the variance explained by fixed effects alone and by fixed and random effects combined, respectively. For the interaction term in Section 4.5.1, the change in marginal R^2 relative to a model omitting the interaction is reported, with both models refitted by maximum likelihood, together with Cohen's f^2 . Additional data management and numerical calculations were performed using pandas, NumPy, and SciPy.

4.5.1 Sleep duration and shift duration

To examine whether the association between sleep duration and recovery percentage varied according to shift duration, a linear mixed-effects model with a physician-specific random intercept was fitted using the final working-day analytic sample. Shift duration was modeled continuously and decomposed into within- and between-physician components. The within-physician component represented the day-to-day deviation of each shift's duration from that physician's mean shift duration, whereas the between-physician component represented the physician-specific mean shift duration centered at the sample mean. Sleep duration was decomposed in the same way into within- and between-physician components. The model included within-physician shift duration, within-physician sleep duration, their

interaction, between-physician mean shift duration, between-physician mean sleep duration, shift type, and consecutive workday. Shift type was included as a categorical covariate, with night shifts as the reference category. The interaction between within-physician shift duration and within-physician sleep duration was used to test whether the within-physician association between sleep duration and recovery changed as physicians worked shifts that were longer or shorter than their own average shift duration.

4.5.2 Shift type, sleep duration, and recovery

Shift type was first modeled in relation to sleep duration. Shift type was represented by indicator variables for afternoon and morning shifts, with night shifts as the reference category, each decomposed into within- and between-physician components. The within-physician components represented day-level deviations from each physician's average shift pattern, and the between-physician components represented differences in overall shift composition across physicians. The model additionally adjusted for shift duration and consecutive workday. The within-physician coefficients for afternoon and morning shifts therefore represent estimated differences in sleep duration relative to night shifts within the same physician. The morning versus afternoon contrast was obtained as the difference between the corresponding within-physician coefficients.

Recovery was then modeled as a function of shift type without sleep duration, using the same decomposition, reference category, covariates, and random-intercept structure, to estimate the total association between shift type and recovery. A subsequent model additionally incorporated sleep duration, decomposed into within- and between-physician components. This model estimated the association between shift type and recovery after accounting for sleep duration and quantified the within-physician association between day-to-day deviations from a physician's usual sleep duration and recovery.

4.5.3 Mediation analysis

Mediation analysis examined whether sleep duration accounted for part of the association between shift type and recovery. Morning, afternoon, and night shifts were retained as distinct categories. Mediator, outcome, and total-effect models were linear mixed-effects models with physician-specific random intercepts, with shift type and sleep duration decomposed into within- and between-physician components, and all models adjusted for shift duration and consecutive workday.

Indirect, direct, and total associations were estimated by applying a physician-level cluster bootstrap with 5,000 resamples, in which physicians were resampled as intact clusters to preserve dependence among repeated observations. Within each resample, the indirect association was computed as the product of the within-physician a and b paths. Direct associations were obtained from the sleep-adjusted recovery model, and model-implied total associations were calculated as the sum of the direct and indirect associations. This definition of the total association is not identical to the unadjusted shift-type coefficient from the outcome model reported in Section 2.2.2; both quantities are reported, and each is labeled explicitly where it appears. Confidence intervals were calculated as 95% percentile intervals

using the 2.5th and 97.5th percentiles of the bootstrap distribution. Resamples that failed to converge were excluded; 4,961 of 5,000 resamples (99.2%) produced successful estimates.

4.5.4 Sensitivity analysis

A residual-correlation sensitivity analysis assessed the extent to which unmeasured mediator-outcome confounding could alter the estimated indirect associations, using estimates from the same random-intercept models. The sensitivity parameter ρ represented the assumed correlation between the remaining Level 1 residual components of sleep duration and recovery, after accounting for the modeled covariates, physician-specific random intercepts, and within- and between-physician decomposition. Values of ρ from -0.80 to $+0.80$ were examined, and the tipping point at which the adjusted sleep-to-recovery association, and consequently the corresponding indirect associations, was reduced to zero was identified. Values reported for this analysis are derived analytically from the model point estimates and therefore differ marginally from the bootstrap medians reported in Section 2.2.3.

Declaration of Generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT (OpenAI) to support language editing, improve the manuscript's clarity and structure, and generate the figures. After using this tool, the authors reviewed and edited the content and take full responsibility for the article.

Declarations

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Data and code availability statement

The de-identified data and the Python codes supporting the findings of this study are available from the corresponding author upon reasonable request. The data and code are not publicly available because they contain potentially identifiable information relating to a small sample of emergency physicians and are subject to institutional data-sharing restrictions.

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Author contribution statement

S.A. conducted the statistical analysis, wrote and edited the manuscript. V.G. worked on conceptualization, developed the hypothesis and wrote and edited the manuscript. T.B. worked on moderating data collection, analysis and edited the manuscript. L.F. worked on moderating data collection, analysis and editing the manuscript. K.T. worked on moderating data analysis and editing the manuscript. E.V. worked on data collection and editing manuscript. S.M. worked on data collection and editing manuscript. S.M. worked on statistical analysis. E.H. worked on moderating data collection, analysis and editing the manuscript.

Competing interests

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this manuscript.

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Figures

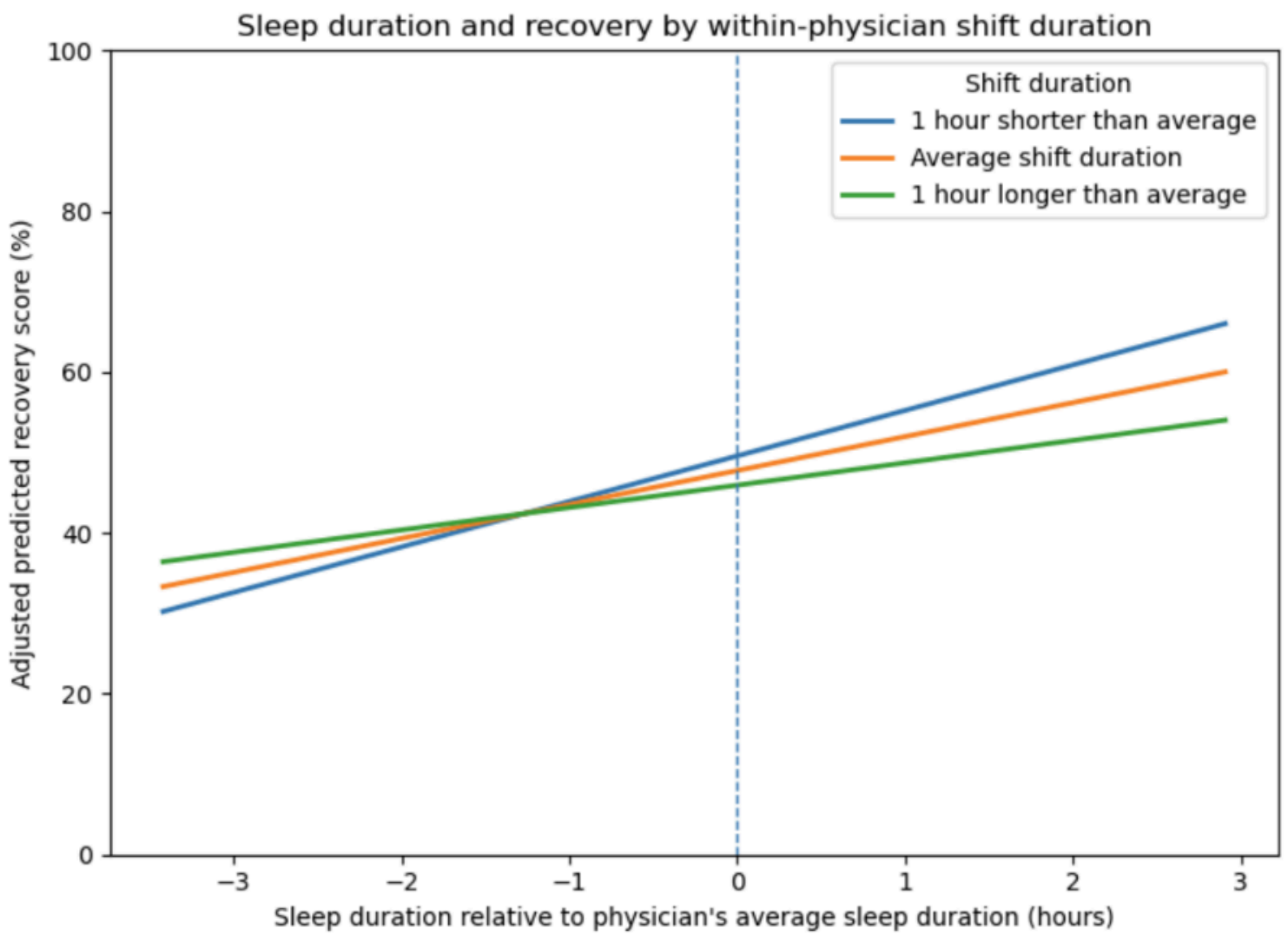


Figure 1

Adjusted predicted recovery scores across within-physician sleep duration for shifts that were 1 hour shorter than the physician’s average shift duration, equal to the physician’s average shift duration, and 1 hour longer than the physician’s average shift duration.

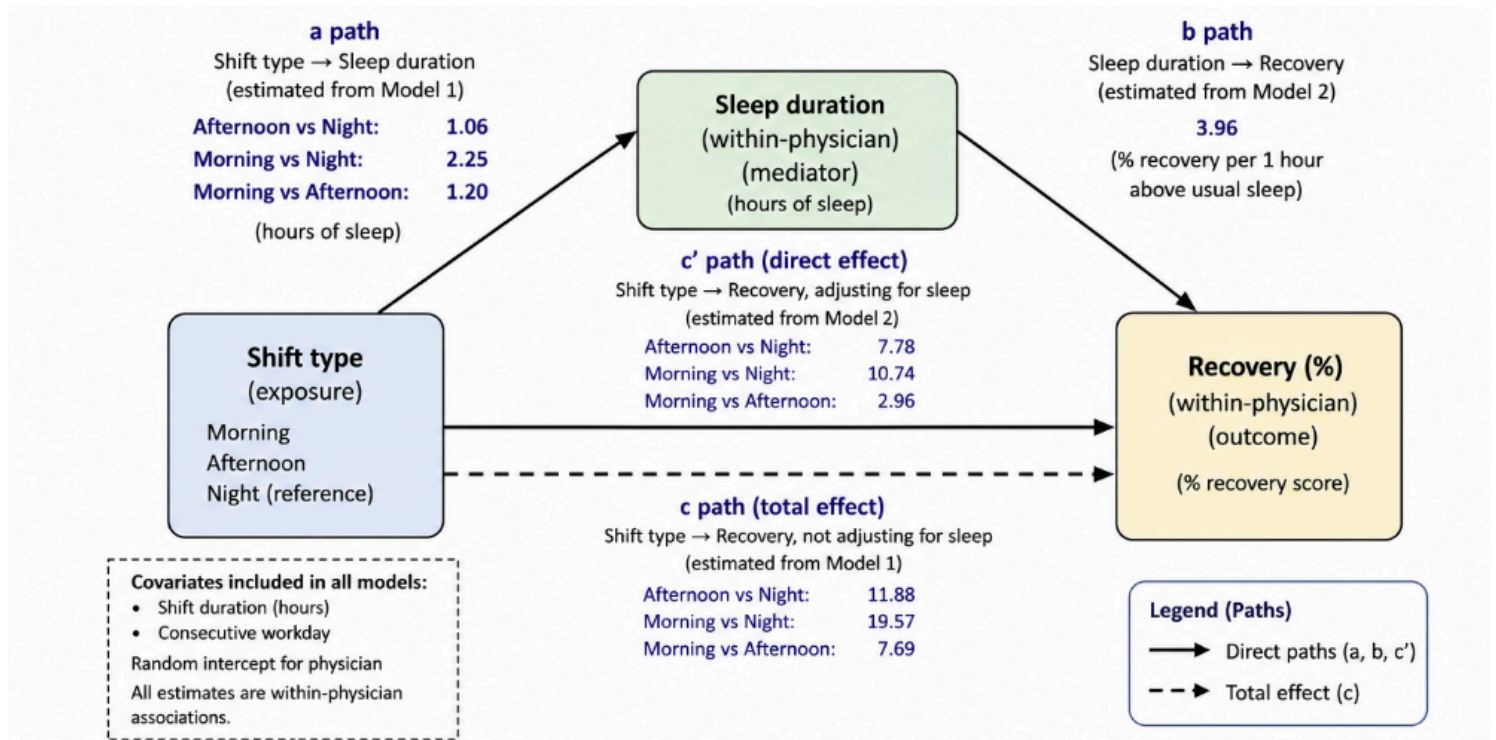


Figure 2

Mediation analysis pathway diagram

Sensitivity of Estimated Indirect Associations to Assumed Residual Mediator–Outcome Correlation

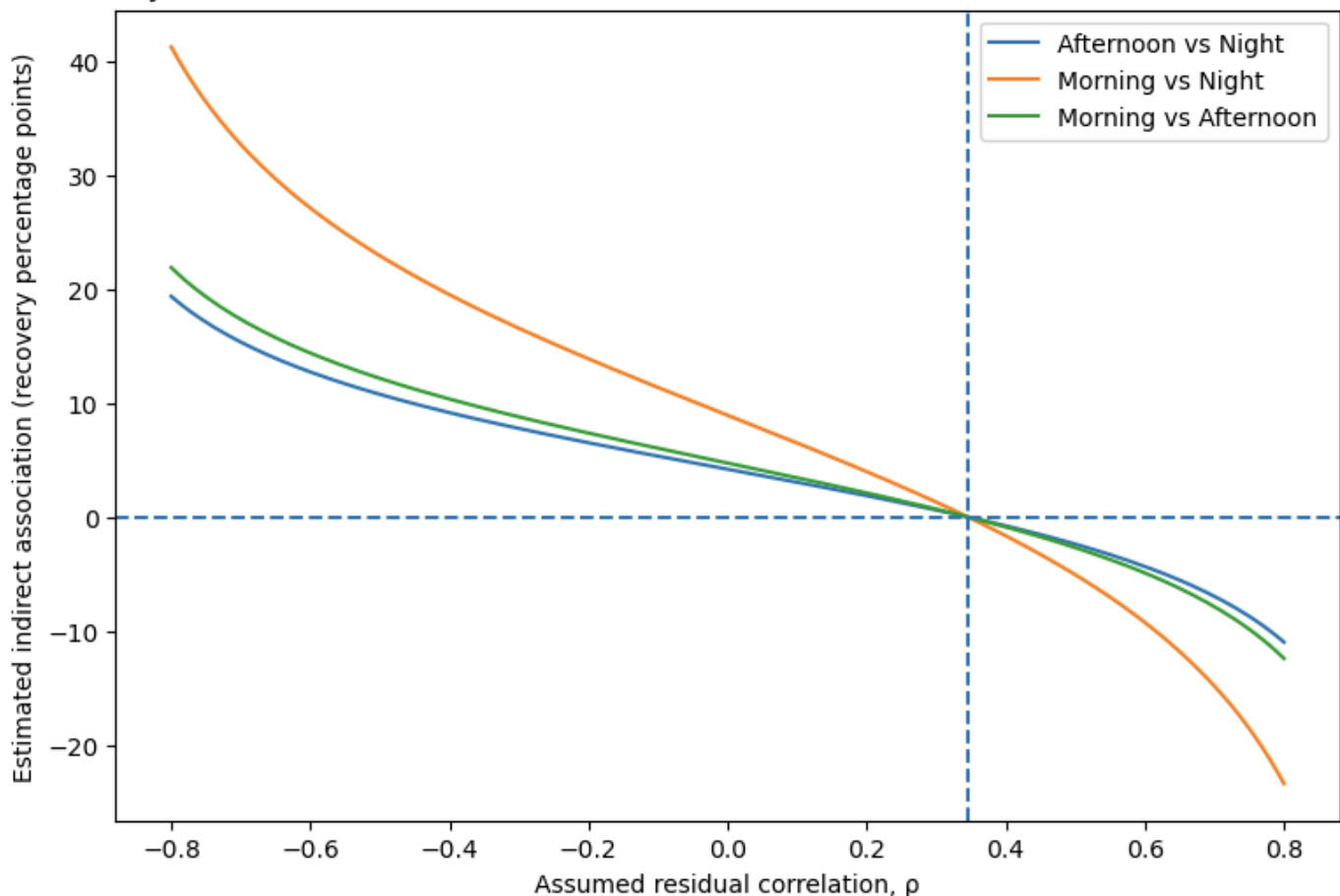


Figure 3

Sensitivity analysis of the estimated indirect associations between shift type and recovery through sleep duration

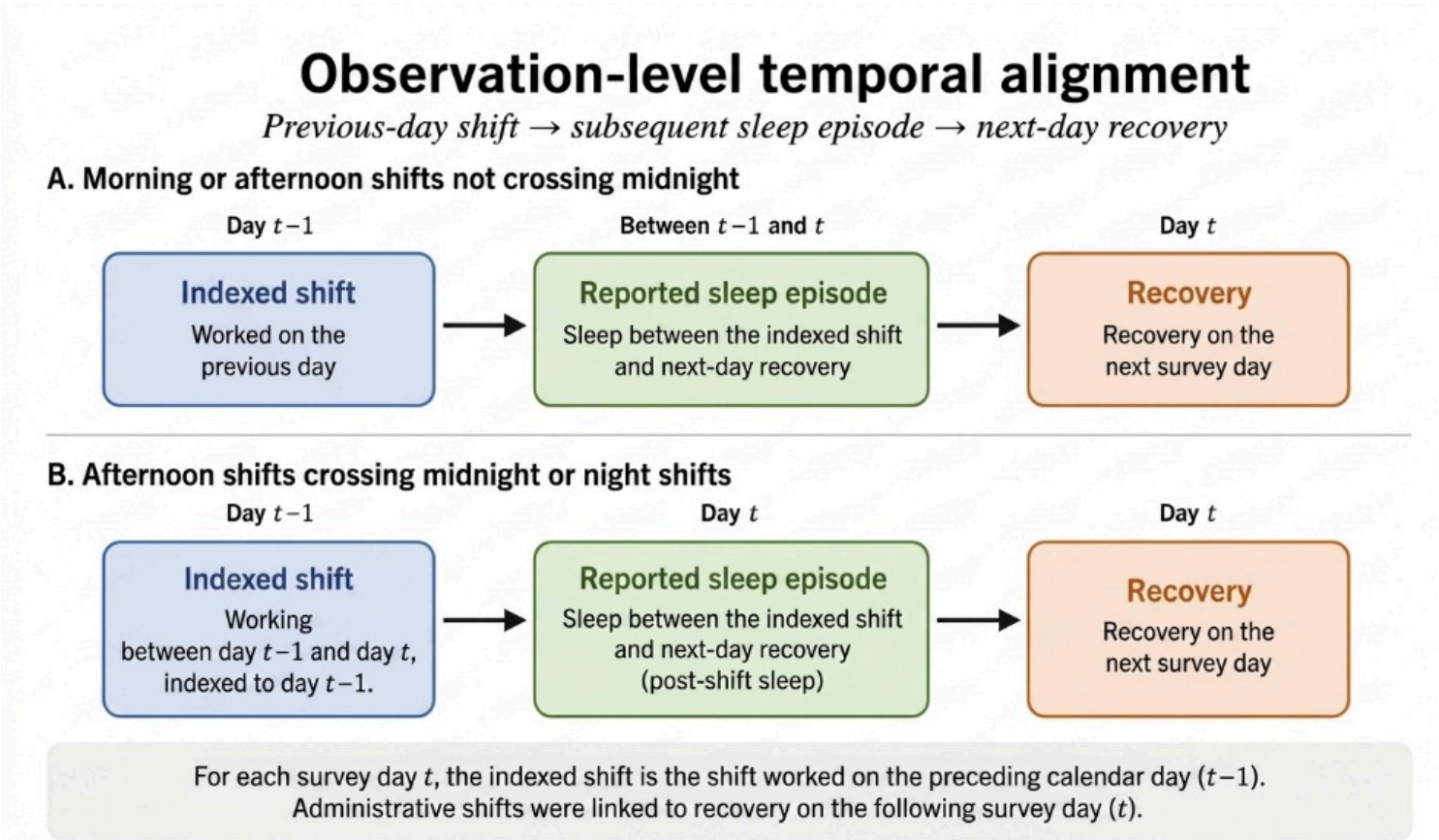


Figure 4

Temporal alignment of the indexed shift, subsequent sleep episode, and recovery.

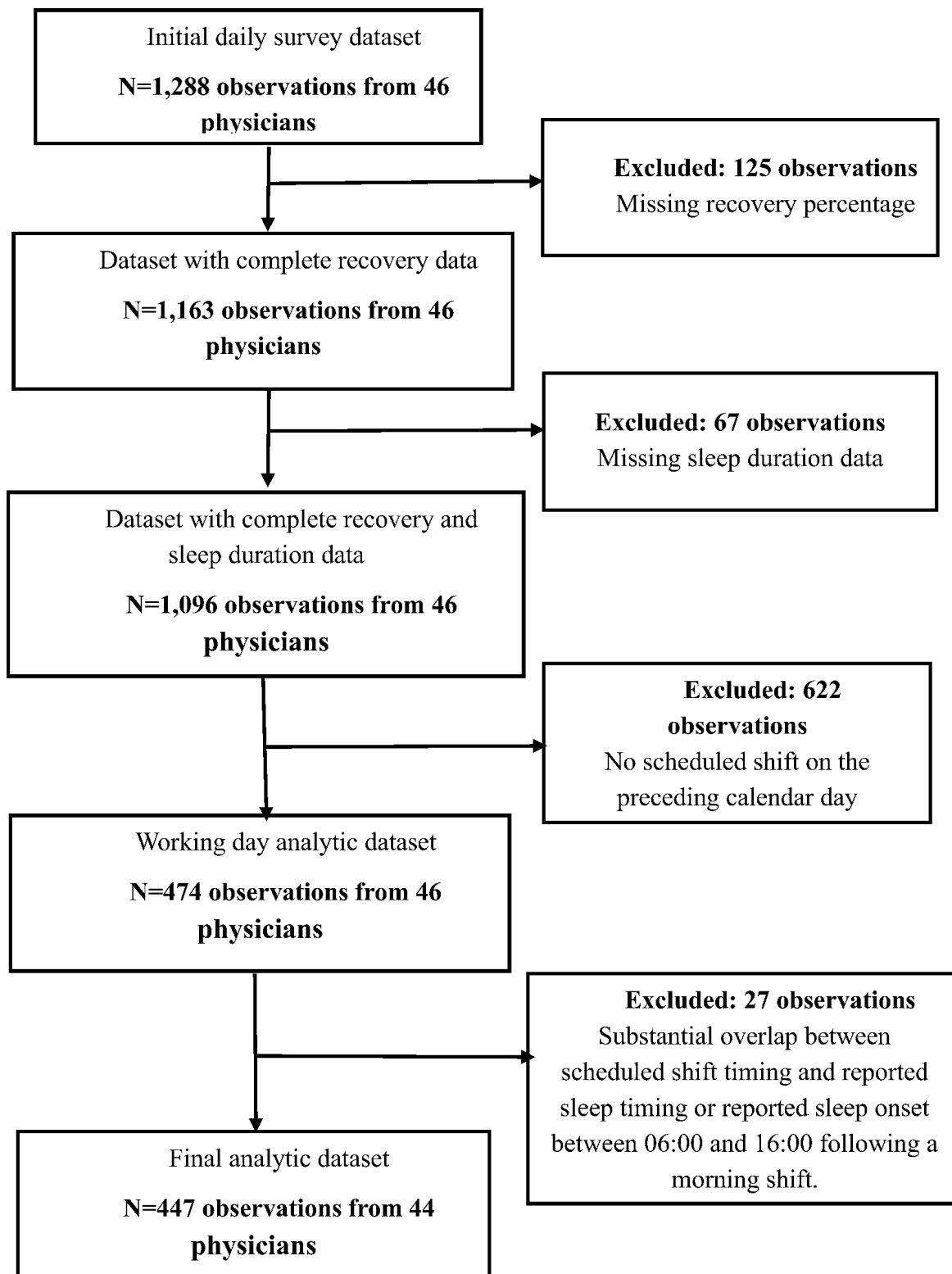


Figure 5

Flow of observations from the initial daily survey dataset to the final analytic dataset