ISSN 2304-3415, Russian Open Medical Journal
2025. Volume 14. Issue 4 (December). Article CID e0401
DOI: 10.15275/rusomj.2025.0401

This article belongs to the Special Topic Collection "Circadian Lighting Hygiene, Health, and Well-being"

Original article

Normalized Amplitude of Blue Light Exposure (NA BLE) as a Novel Index for Circadian Light Hygiene: Associations with Actigraphy Measures and Seasonal Dependencies

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Received 17 September 2025, Revised 10 October 2025, Accepted 18 October 2025

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Abstract: *Background* — Light exposure (LE) critically regulates circadian rhythms, influencing sleep, mood, metabolism, and longevity. Quantifying circadian light hygiene is challenging due to high inter-individual variability. The Normalized Amplitude of Blue Light Exposure (NA BLE) metric provides a standardized assessment of BLE dynamics and range. We evaluated NA BLE in high-latitude Arctic residents, leveraging extreme seasonal light variations as a natural experiment to characterize its seasonal dependencies and associations with circadian parameters.

Methods — Twenty-seven healthy Arctic adults underwent longitudinal assessment across seasons, spanning winter solstice, spring equinox, and summer solstice. Wrist actigraphy (ActTrust 2) captured physical activity (PA), wrist temperature (wT), light exposure (LE), and blue light exposure (BLE).

Results — NA BLE exhibited clear seasonal variation, with a peak in spring and a nadir in winter, showing consistent patterns across sexes and populations (irrespective of indigeneity). Larger NA BLE correlated positively with indicators of circadian robustness, including Circadian Function Index (CFI) ($p<0.0001$), PA ($p=0.001$), and Inter-Daily Stability ($p=0.008$). Conversely, smaller NA BLE was associated with later circadian timing markers such as L5 onset of PA and BLE ($p<0.001$), bedtime ($p=0.007$), and lower stability of non-parametric actigraphy measures.

Conclusions — Larger NA BLE significantly correlates with enhanced circadian robustness and healthier circadian timing, demonstrating its value despite seasonal fluctuations. NA BLE reliably measures circadian light hygiene, unaffected by sex or population subgroup. These results validate its utility in Arctic settings and advocate for its broader application in light exposure assessments to advance public health.

Keywords: circadian, light exposure, blue light, circadian light hygiene, actigraphy, Arctic, seasonality, NA BLE, chronobiology.

Cite as Gubin DG, Boldyreva JV, Danilova LA, Kolomeichuk SA, Alkhimova LE, Markov AA, Malyugina OA, Kuznetsova NV, Stefani O, Weinert D, Cornelissen G. Normalized amplitude of blue light exposure (NA BLE) as a novel index for circadian light hygiene: Associations with actigraphy measures and seasonal dependencies. *Russian Open Medical Journal* 2025; 14: e0401.

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Introduction

The intricate interplay between light exposure and endogenous circadian rhythms underpins human health and well-being. Adequate circadian light hygiene – characterized by appropriate timing, intensity, and spectrum of light exposure [1, 2] – is essential for maintaining robust circadian function, which influences sleep, mood, metabolism, and overall longevity [3-7]. Measuring circadian light hygiene effectively remains challenging. Absolute measures of light exposure, while informative, often exhibit substantial inter-individual variability, hindering cross-contextual comparisons. To address this, the Normalized Amplitude of Light Exposure (NA LE), specifically for Blue Light Exposure (NA BLE), has been proposed as a practical and standardized metric [3, 4, 8, 9]. NA BLE quantifies the dynamic range of light exposure in a standardized manner, thereby facilitating more reliable comparisons across individuals and environments.

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Extreme seasonal light variation in high-latitude Arctic environments provides a unique natural experiment to evaluate metrics like the Normalized Amplitude of Blue Light Exposure (NA BLE). Although pronounced seasonal shifts in daylight significantly impact circadian entrainment and behavior [9-14], the direct dependence of NA BLE on seasonal light abundance is not immediately obvious. To rigorously assess NA BLE's utility in circadian light hygiene, this study sought to: 1) quantify seasonal dependencies of NA BLE in Arctic residents, 2) examine associations of NA BLE with actigraphy-derived circadian rhythm parameters, and 3) investigate potential moderation by sexes and subgroups.

Material and Methods

Study Population and Design

A longitudinal study was conducted with 27 healthy adult residents of high Arctic latitudes, where pronounced seasonal variations in natural light exposure create a unique environmental context. Participants provided written informed consent, and the study protocol was approved by the relevant institutional review board. Data collection occurred across three seasonal periods: winter solstice, spring equinox, and summer solstice.

Measures

All participants maintained sleep diaries and wore wrist actigraphy devices (*ActTrust 2*, Condor Instruments, São Paulo, Brazil) on their non-dominant wrist for continuous monitoring during the study period. Motor activity was quantified using the Proportional Integrative Mode (*PIM*), which measures movement intensity by summing voltage deviations from baseline every 0.1 second, aggregated over 1-minute epochs, and correlates strongly with polysomnography-derived sleep parameters. Physical activity (*PA*), wrist temperature (*wT*), light exposure (illuminance at the wrist in lux, *LE*), and blue light exposure (illuminance at the wrist in µW/cm², *BLE*) were recorded at 1-minute intervals via the *ActTrust 2* sensors.

From the actigraphy data, parametric measures – including *MESOR*, 24-hour amplitude, and acrophase – were estimated for *PIM*, *wT*, *LE*, and *BLE*. Non-parametric indices were derived using validated algorithms in *ActStudio* software (Condor Instruments, São Paulo, Brazil), as previously described [8-14]. These included inter-daily stability (IS), intra-daily variability (IV), relative amplitude (rA) for PA, LE, and BLE, circadian function index (CFI) [15], the maximum 10-hour window (M10) and its onset, the least 5-hour window (L5) and its onset for PA and BLE, BLE phase, bedtime, wake time, total sleep duration (TSD), and wake after sleep onset (WASO). The variability of most parameters was quantified by their standard deviation (*SD*), also output by *ActStudio*. The relative amplitude of *BLE* (*rA BLE*) was computed as (*M10 BLE – L5 BLE)* / (*M10 BLE + L5 BLE*), reflecting the proportional difference between the highest 10-hour *BLE* period and the lowest 5-hour *BLE* period. The normalized amplitude of *BLE* (*NA BLE*), defined as the ratio of the 24-hour amplitude of the best-fit cosine curve to its *MESOR*, was calculated as previously outlined [3, 4, 8, 9]. This metric standardizes the dynamic range of *BLE* to account for individual baselines, thereby minimizing inter-individual variability.

Seasonal variations in *NA BLE* were evaluated using Friedman's ANOVA, a non-parametric test appropriate for repeated measures across more than two conditions. Post-hoc pairwise comparisons were performed using Wilcoxon signed-rank tests as needed. The Kendall coefficient of concordance (*W*) assessed overall agreement in seasonal rankings of *NA BLE*. Associations between *NA BLE* and actigraphy-derived circadian parameters were explored via linear regression, conducted both overall and stratified by season. A threshold of $|r|>0.21$ was established as the minimum effect size for practical significance in Pearson correlations in this study, prioritizing biologically meaningful relationships after adjusting for multiple comparisons. Thus, correlations were deemed significant at $p<0.05$ with $|r|>0.21$ following Benjamini–Hochberg false discovery rate correction at FDR=0.1. The moderating effects of sex and population subgroup were examined using two-way ANOVA to test any significant interactions between season and sex, as well as season and population subgroup.

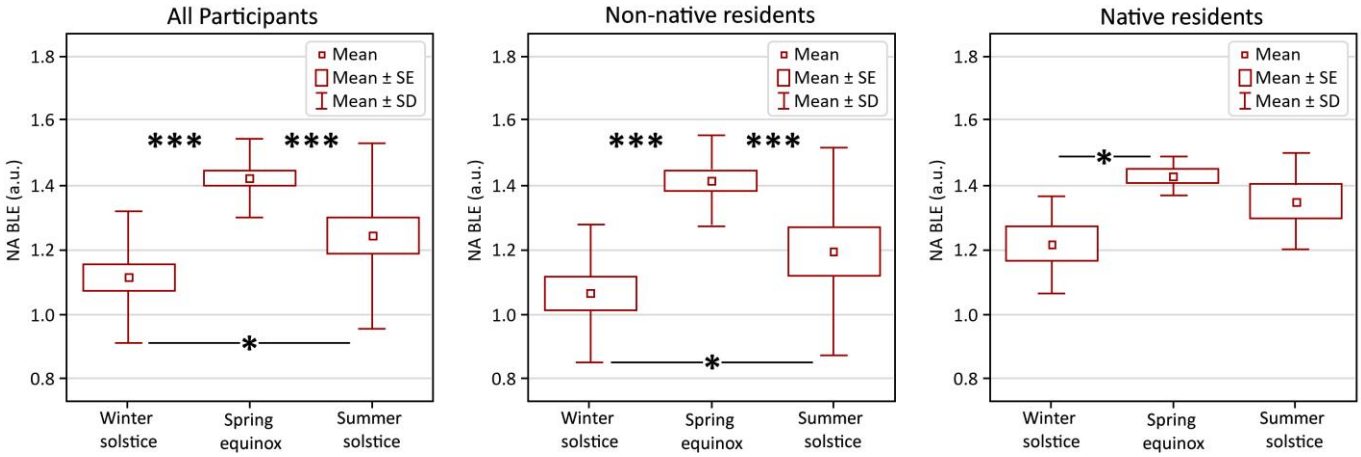

Figure 1. Seasonal Variation of Normalized Amplitude of Blue Light Exposure (NA BLE) in Arctic Residents

Seasonal patterns of NA BLE, assessed in winter, spring, and summer, are depicted in the figure. NA BLE exhibited significant seasonal variation, peaking in spring. This pattern was observed to be proportional across seasons in both native and non-native Arctic residents, indicating similar temporal dynamics in blue light exposure patterns irrespective of residency status. Significant differences (determined via Wilcoxon signed-rank test) are shown as *** ($p<0.001$), ** ($p<0.01$), and * ($p<0.05$).

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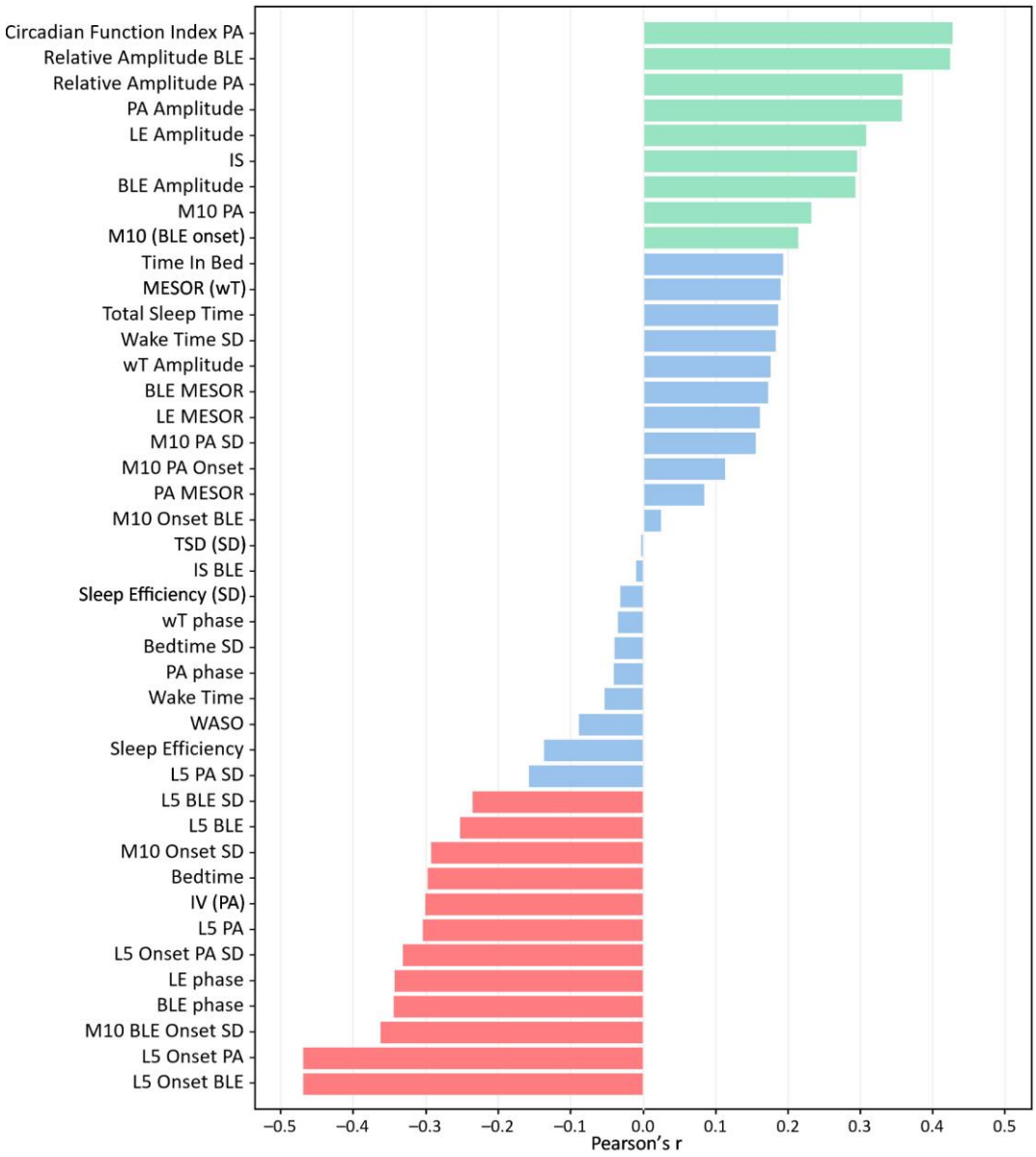

Figure 2. Associations Between Circadian Rhythm Parameters and Normalized Amplitude of Blue Light Exposure (NA BLE).

This figure displays Pearson correlation coefficients (*r*) examining the relationships between NA BLE and various circadian rhythm parameters. Statistically significant correlations ($p < 0.05$) are shown in green (positive) or red (negative). A total of 9 significant positive correlations and 12 significant negative correlations were observed. Green bars indicate statistically significant positive correlations ($r>0.21$), implying a concordant relationship with indices considered beneficial for circadian health. Red bars indicate statistically significant negative correlations ($r<-0.21$), suggesting an association with indices that may pose potential risks to circadian health. BLE, Blue Light Exposure; PA, Physical Activity; L5, least active 5-hour period; M10, most active 10-hour period; SD, standard deviation; MESOR, midline estimating statistic of rhythm; IS, inter-daily stability; IV, intra-daily variability; wT, wrist temperature; WASO, wake after sleep onset; TSD, total sleep duration.

Results

Seasonal Dynamics of Normalized Amplitude of Blue Light Exposure (NA BLE)

Despite NA BLE being a normalized metric, which might not intuitively suggest dependence on seasonal light quantities, our analysis revealed significant seasonal variations. A non-parametric Friedman's ANOVA demonstrated a significant effect of season on NA BLE (χ^2=16.074, p<0.001). The Kendall coefficient of concordance further corroborated the high degree of agreement in these seasonal patterns across participants (W=0.298; p=0.001). Mean NA BLE values differed significantly by season, with spring (M=1.417, SD=0.120) exhibiting the highest value, followed by summer (M=1.239, SD=0.288) and winter (M=1.110, SD=0.204). Pairwise comparisons between seasons, conducted using the Wilcoxon signed-rank test (results depicted in *Figure 1*), confirmed significant differences across seasons. To assess robustness, we examined potential interactions using two-way ANOVAs. Specifically, no significant interaction was found between season and sex (F=1.355; p=0.248) or season and indigeneity subgroup (natives *vs.* non-natives) (F=0.081; p=0.922). This result indicates that the observed seasonal pattern of NA BLE was not modulated by participants' sex or subgroup affiliation.

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Associations between NA BLE and Actigraphy-Derived Circadian Parameters

Linear regression analyses conducted across all seasons revealed significant associations between NA BLE and a range of actigraphy-derived circadian rhythm parameters. A total of 9 significant positive correlations and 12 significant negative correlations were identified (see *Figure 2* for a detailed overview).

Positive Associations with Circadian Robustness and Beneficial Health Indices: NA BLE demonstrated statistically significant positive correlations with indices considered indicative of robust circadian function and health. Specifically, a larger NA BLE was associated with a higher Circadian Function Index (CFI) (r=0.428; p<0.0001), a greater non-parametric relative amplitude of BLE (rA BLE) (r=0.424; p<0.0001), and a greater non-parametric relative amplitude of physical activity (rA PA) (r=0.359; p=0.001), as well as parametric circadian amplitudes of PA (r=0.358; p=0.001), LE (r=0.307; p=0.005), BLE (r=0.294; p=0.008), and higher inter-daily stability (IS) (r=0.295; p=0.008). NA BLE was also associated with measures of higher daytime PA, M10 (r=0.232; p=0.038), and BLE M10 (r=0.218; p=0.048). These findings suggest that individuals with a larger amplitude of their BLE exhibit more stable and robust circadian rhythms.

Negative Associations with Parameters Indicative of Hazardous Circadian Timing: In contrast, NA BLE exhibited significant negative correlations with circadian timing parameters often associated with health risks. Smaller NA BLE values were associated with later L5 onsets of BLE (r=-0.470; p<0.001) and PA (r=-0.468; p<0.001), later BLE phase (r=-0.344; p=0.002) and LE phase (r=-0.343; p=0.002), and later L5 of PA (r=-0.303; p=0.006) and BLE (r=-0.253; p=0.023). Smaller NA BLE values were also associated with later bedtime (r=-0.299; p=0.007) and greater variability in overall PA, as measured by IV (r=-0.300; p=0.007) and SD of M10 onsets for BLE (r=-0.363; p<0.001), PA (r=-0.292; p=0.008), L5 onset for PA (r=-0.331; p=0.003), and L5 for BLE (r=-0.235; p=0.035). These associations suggest that a greater BLE dynamic range is linked to more robust circadian rhythms and healthier (*e.g.*, earlier) circadian timing.

To evaluate the reliability of the statistical findings given the limited sample size (n=27), we conducted post-hoc power analyses for key tests. Power estimates were calculated for the Friedman's ANOVA examining seasonal differences in NA BLE (χ^2=16.074, df=2, W=0.298), yielding a power of approximately 0.82. For pairwise seasonal comparisons using Wilcoxon signed-rank tests (*e.g.*, spring *vs.* winter, mean difference=0.307, SD=0.120 and 0.204), power ranged from 0.75 to 0.80 for the observed effect sizes. Correlation analyses between NA BLE and circadian parameters (with r values ranging from 0.218 to 0.470) yielded power estimates of 0.50-0.95, varying with the strength of the association. For interactions in two-way ANOVA (season × sex, season × ethnicity), power was estimated at 0.40-0.55 based on observed F-statistics. All power calculations were performed using G*Power software (version 3.1; [16]), with α=0.05 and two-tailed tests where applicable. These analyses enhance confidence in detecting moderate to large effects while highlighting the risk of type II errors for smaller effects.

Discussion

This study establishes NA BLE as a robust, standardized index for evaluating circadian light hygiene. In a high-latitude Arctic setting with extreme seasonal light fluctuations, NA BLE displayed predictable seasonal patterns, with greater amplitudes observed in spring than in winter or summer. These fluctuations were closely coupled to adverse seasonal changes in lipid metabolism [9-11], eating behavior [17], and compromised circadian robustness after COVID-19 [8, 18], as previously described.

NA BLE further showed strong associations with actigraphy-derived circadian rhythm parameters. Positive correlations with established indices of circadian robustness, including measures of PA such as CFI, RA, and IS, align with extensive literature linking these parameters to improved health outcomes and longevity [6-7, 19-37]. Specifically, larger amplitudes of PA and LE are recognized as crucial indicators of circadian robustness, which are associated with better health [3-5, 8-9, 11-12, 37-43], while loss of regularity is linked to multiple health risks [3, 4, 21, 22, 43-48]. Conversely, negative correlations with parameters indicating hazardous circadian timing, such as L5 onset of BLE, BLE phase, and bedtime, reinforce the established association between later circadian timing and increased health risks [1-11, 22-23, 50-52].

NA BLE's pronounced seasonality is inherently linked to photoperiodic conditions. While consistent patterns emerged in our cohort, extending NA BLE assessments to populations experiencing less extreme seasonal light variations is essential to evaluate its broader applicability. Moreover, although the correlational findings are significant, they preclude causal inferences or predictions of specific health outcomes. The modest sample size (n=27) limits statistical power and heightens the risk of Type II errors, especially for detecting small to moderate effects. Post-hoc power analyses using G*Power revealed adequate power (~0.82) for detecting the observed seasonal differences in normalized blue light amplitude (NA BLE) via Friedman's ANOVA. Moderate to high power (0.75-0.95) was attained for correlations with circadian parameters, contingent on effect size. However, power was substantially lower (0.40-0.55) for interaction effects in two-factor ANOVA, indicating reduced sensitivity to subgroup differences by sex or ethnicity. Thus, some subtle associations or interactions may remain undetected. To bolster generalizability and mitigate these limitations, future studies should employ larger, more diverse cohorts to validate and expand these findings, enhance applicability, and elucidate potential moderating effects. Specifically, future investigations should prioritize: (1) cross-validating NA BLE in diverse populations under varying photoperiodic conditions, (2) conducting longitudinal studies to assess its predictive value for health outcomes, and (3) evaluating its utility in designing targeted clinical and public health interventions for circadian health management.

Conclusion

Collectively, these findings robustly suggest that NA BLE is highly sensitive to seasonal light variations and serves as a reliable correlate of healthy circadian alignment. Its ability to capture key aspects of light exposure's dynamic range, coupled with strong associations with both beneficial circadian rhythm parameters and those indicating potential circadian maladaptation, underscores its potential as a valuable tool for monitoring and promoting circadian health across diverse settings.

Conflict of Interest

The authors declare no conflicts of interest.

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Funding

This study was supported by the West-Siberian Science and Education Center, Government of Tyumen Oblast, Decree of November 20, 2020, No. 928-rp.

Ethical Approval

All procedures involving human participants were conducted in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards.

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