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Review

Actigraphy for quantitative evaluation of health

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Abstract: An analysis of large-scale studies utilizing actigraphy and wearable devices for continuous monitoring of physiological measures was conducted. Data had been obtained from the UK Biobank and the National Health and Nutrition Examination Survey (NHANES) for use in the studies. The link between circadian rhythm deviations and health status was investigated. The amplitude and phase of circadian rhythms, along with variability parameters of physical activity, skin temperature, and light exposure, were found to be informative markers of key health indicators, including morbidity, mortality, and life expectancy. These findings highlight the critical role of circadian markers – amplitude, phase, and variability – in predicting health risks related to metabolic and sleep disorders, emotional well-being, and cognitive function. By exploring nonlinear associations between chronotype and health risks, we propose that personalized adjustment of sleep-wake phase, based on light hygiene and physical activity regimes and taking into account age, sex, and genetic cofactors, may contribute to the advancement of health-preserving technologies and the extension of human lifespan.

Keywords: actigraphy, health monitoring, large databases, circadian rhythm, chronobiology, light, activity, temperature, longevity.

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Introduction

Circadian rhythms patterns and variability are key indicators of health [1-8]. A variety of methods are employed to analyze such variability, aiming to assess deviations from optimal values and to use this information for early identification of health risks and optimization of preventive strategies. This approach forms the foundation of the increasingly recognized field of *circadian medicine* [1, 4, 6-8]. In circadian studies, wearable technologies provide unique opportunities for tracking sleep, activity, temperature, heart rate, and other physiological measures. This allows for a quantitative analysis of the circadian rhythms and non-circadian variability, which helps identify health risks. Despite the wide variety of multi-sensor wearable devices available today, actigraphy remains the most validated and widely used tool for comprehensive chronobiological analysis of sleep, physical activity, and body temperature [9, 10]. Next-generation actigraphs also assess light exposure dynamics across spectral ranges [11].

By providing such comprehensive information, actigraphy has become a widely used tool. Today, it is applied not only for the assessment of sleep, but also in the study of neurodegenerative disorders, cardiovascular and metabolic health, and circadian rhythm disorders [12, 13]. Actigraphy measurements correlate with blood glucose levels, insulin sensitivity, and lipid profile [14-19]. The integration of actigraphy and biobank data offered an opportunity to explore links between lifestyle, genetics, and metabolic health. These findings advance chronobiological understanding of disease and inform public health strategies. Actigraphy also helps evaluate preventive measures and interventions to improve sleep and increase physical activity, thereby enhancing health technologies and treatment outcomes.

This review estimates the complex relationships between disrupted circadian rhythm and health outcomes, furthering our understanding of circadian rhythms' role in human health and longevity. The search, conducted in PubMed, focused on studies using large actigraphy datasets to assess alterations in circadian variability and sleep as markers of morbidity, mortality, overall health, and life expectancy.

Results. Circadian markers of morbidity and mortality

The decline in circadian robustness, observed with aging and in pathology, has long been recognized as a marker of biological age and a predictor of healthy aging and longevity [4, 6, 7, 19-21]. This concept remains widely accepted among leading scientific groups [1-3]. Until recently, supporting evidence for this hypothesis was primarily drawn from small-scale, often laboratory-based studies. Retrospective and prospective analyses of large-scale actigraphy

datasets from the UK Biobank [22] and the US National Health and Nutrition Examination Survey (NHANES) [23] now offered strong real-world evidence, opening new avenues for chronobiological health markers in personalized healthcare.

The circadian rhythm of physical activity plays an important role in maintaining physical health [24]. A retrospective analysis of actigraphy data from the UK Biobank (over 100,000 participants aged 40 to 69 years) found that a higher circadian amplitude of physical activity was associated with a lower risk of various health problems, including cardiovascular, metabolic, respiratory, infectious, cancer, and other conditions [25]. Similar results were reported in a 16-year prospective study involving 1,000 adults [26]. Moreover, actigraphy data from more than 100,000 participants revealed that 73 out of the 423 (17%) disease phenotypes were significantly associated with a reduction in the circadian amplitude of wrist temperature. The strongest associations were observed for type 2 diabetes, non-alcoholic fatty liver disease, hypertension, and pneumonia [27]. Lower circadian amplitude and reduced circadian stability were also associated with increased susceptibility to mood disorders, such as major depressive disorder and bipolar disorder, as well as mood instability and neuroticism [28]. Similar circadian rhythm disruptions predicted cognitive impairment in Alzheimer's and Parkinson's diseases [29, 30]. Among Japanese adults, higher relative amplitude of wrist skin temperature and lower temperature fragmentation (lower intradaily variability [IV] and higher interdaily stability [IS]) were associated with better sleep quality [31]. Other circadian markers of morbidity and mortality include deviations in circadian phase and nonparametric estimates such as the onset of the 10-hour period of peak activity (M10) and the 5-hour period of lowest activity (L5) (*Table* 1). For instance, later peak activity has been associated with increased mortality from cancer and stroke [32], as well as with a higher risk of dementia and cognitive impairment in older women [33]. In the UK Biobank study involving 88,282 adults, an earlier or later onset of the L5 period – outside the intermediate range of 3:00-3:29 AM – as measured through 7-day actigraphy, was associated with a 20% increased risk of all-cause mortality [34]. Another UK Biobank study on 103,712 participants showed that sleep onset time earlier or later than the optimal 10:00-11:00 PM interval was associated with cardiovascular disease (CVD) risk, particularly in women [35]. Given that both L5 onset and sleep mid-time serve as chronotype markers, these studies demonstrate a non-linear relationship between chronotype and health risks, with both extreme evening and extreme morning types exhibiting significantly higher risks. Because chronotype shifts within the 40-70 age range are sex-specific [36], further detailed analyses of the UK Biobank cohort (which is exclusively comprised of individuals within this range) are needed, and should adjust relevant metrics from large databases for age, sex, population characteristics, and geographical region. These adjustments may be useful in evaluating the possibility of identifying an optimal circadian phase position, particularly in light of the *circadian resonance* concept, which proposes that longevity is linked to a closer alignment between the endogenous circadian period and the 24-hour day. This alignment is thought to be more common among individuals with an intermediate morning chronotype [37-38].

Actigraphy represents a promising chronobiological approach to the quantitative assessment of metabolic risks associated with obesity and diabetes [19, 15-18, 41]. Several circadian markers have been associated with metabolic disturbances, including lower circadian amplitude and delayed acrophase [16], misalignment between light exposure and activity patterns [17, 41], and poor circadian light hygiene, such as excessive evening light exposure [18, 19]. Our self-measurements study showed that amplitude and phase alterations of the 24-h body temperature rhythm, already present in patients with prediabetes, were even more prominent in diabetic patients [39]. An analysis of UK Biobank data involving 84,790 participants examined light sensor data collected continuously over one week [40]. This study found that increased risk of type 2 diabetes was associated with brighter nighttime light exposure, lower circadian rhythm amplitude, and delayed circadian phase – independent of genetic predisposition. Although lower daytime light exposure was also linked to increased diabetes risk, this association lost statistical significance after controlling for physical activity. Given the known effects of both physical activity and daylight on circadian amplitude and stability [24], this suggests that the amplitude–phase characteristics of physical activity may mediate the association between 24-hour light exposure and diabetes risk. Coordinated circadian rhythms of physical activity and sufficient daylight exposure contribute to a higher amplitude and stability of circadian rhythms, including body temperature rhythms [24]. Conversely, low-amplitude and phase-shifted activity rhythms have been associated with mood disorders such as depression [42-44] and binge eating disorder [45]. Among young adults fragmented motor activity has been linked to food addiction and emotional eating [46].

Besides amplitude and phase parameters, mean and interval-averaged physical activity, light exposure, and skin temperature are further markers of health risks and disease. These interval-averaged values are calculated for 24-hour cycles, daytime, nighttime, or other defined recording periods. The interpretation of results depends critically on the selected time frame: for instance, low daytime activity and high nighttime light exposure are linked with health hazards [19]. Moreover, it can be causally linked to elevated activity during the night is typically associated with sleep disturbances.

Health risks associated with circadian disruption, beyond reduced amplitude, include deviations from sinusoidality, phase delays, phase instability, and rhythm fragmentation. Phase instability caused by inadequate light exposure or altered sensitivity to light disrupts the coherence of circadian rhythms [7, 19-20, 47-49]. Phase delays, such as a delayed sleep-wake cycle, are a common health risk factor. It is primarily influenced by the 24-hour pattern of light exposure, including its intensity and spectral characteristics, as well as genetic factors linked to chronotype [37]. Phase instability and irregular sleep-wake patterns have also been associated with increased mortality risk [50].

Identifying disease-specific risk markers may be facilitated by focusing on time windows of physiological susceptibility or responsiveness. Various methods have been applied to assess these periods and several approaches have been proposed to evaluate 24-hour light exposure profiles. These approaches include:

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Table 1. Actigraphy diagnostic markers

Parameter	Examples of measured quantities	Nature of alterations	Refs
Means	Increase or decrease in MESOR, M10, L5	Psychophysiological, behavioral and genetic factors	[2, 14-16, 26, 29, 30, 40, 42, 45, 46]
Circadian Amplitude	Decrease in circadian rhythm amplitude, Relative Amplitude (RA), and Normalized Amplitude (NA)	Low physical activity, decreased sleep quality, lack of daylight, excess evening and night light, melatonin deficiency, etc	[15, 16, 26-28, 30, 31, 40, 42-45, 58]
Phase shifts (usually phase delay)	Circadian phase, midpoint, sleep onset and offset phases, M10 / L5 time for activity and light exposure	Chronotype, genetic factors, lack of daylight, excess of evening and night light	[16, 17, 26, 32, 34, 35, 40, 43, 44]
Phase coherence between rhythms	Variation in the optimal phase angle values between rhythmic functions	Loss of optimal connections between physiological functions within the time window, such as changes in the optimal temporal coherence between light and activity, sleep and melatonin, sleep and temperature	[18, 41, 48]
Variability structure	Rhythm fragmentation, reduced phase stability, changes in the spectral composition of rhythms, irregularity, and rigidity.	Decreased amplitude of the 24-h light rhythm or reduced light perception, functional disorders of peripheral organs	[26, 30, 31, 46, 49, 50, 56]
Indexes	Area above (or below) the reference curve, scalar regression, and composite indices	Systemic and local changes during sleep-wake transitions, time intervals of increased sensitivity to the factor	[18, 19, 54, 55, 58]

M10, 10-hour period of peak activity; L5, 5-hour period of lowest activity; RA=(M10-L5)/(M10+L5); NA=A/M, where the values at a moment of time: $y(t)=M+A*\cos(2nt/\tau+\phi)$; τ, period; ϕ, acrophase (the peak time of the rhythm); MESOR, Midline Estimating Statistic of Rhythm (the average level of the rhythm); A, amplitude.

1. Quantification of the areas above and below the optimal 24-hour light exposure curve, referred to as the *Nocturnal Excess Index (NEI)* [52] and the *Daylight Deficiency Index (DDI)* [53], respectively. Threshold values for these indices are based on consensus guidelines for circadian light hygiene [51];
2. *The MLiT500 metric*, which represents the average duration of time intervals during which illuminance exceeds 500 lux [54];
3. *The Function-on-Scalar Regression* (FOSR) method, which is used to detect temporal differences in light exposure profiles between groups stratified by the presence or absence of a particular risk factor or pathology [55].

Both the NEI and MLiT500 have demonstrated prognostic significance for body mass index. Moreover, nocturnal blue light excess, as measured by NEI, was associated with adverse metabolic alterations occurring between 09:30 AM and 00:30 PM. These effects were more pronounced among carriers of the MTNR1B rs10830963 melatonin receptor gene polymorphism. The DDI was associated with elevated cortisol levels in Arctic spring conditions [8, 19]. Furthermore, the FOSR method identified daytime and evening intervals of heightened and more variable activity, which were predictive of Alzheimer's disease in individuals with positron emission tomography–confirmed beta-amyloid (Aβ) deposition [55]. Irregular light exposure, particularly when accompanied by decreased sleep regularity, has been identified as a cofactor in the development of atherosclerosis [56]. In contrast, human-centric light exposure, personalized by chronotype, has been shown to exert beneficial effects on circadian rhythms and sleep in patients with Parkinson's disease [57].

Emerging digital biomarkers from wearables—including amplitude, phase, and variability metrics of circadian rhythms and physical activity—offer promising tools for preventive circadian medicine, biological age assessment, and anti-aging intervention [58].

Conclusion

This literature review underscores the value of actigraphy and wearable devices in quantifying human health. Large databases enable researchers to explore links between specific types of circadian disruption and health outcomes. Key indicators, including circadian rhythm amplitude, phase, and variability metrics, may serve as biomarkers for morbidity, mortality, and lifespan, correlating with conditions ranging from metabolic disorders to cognitive dysfunction. Investigating nonlinear relationships between chronotype, light hygiene, and genetic risk factors may facilitate personalized circadian entrainment strategies, such as optimized light and activity regimens. Accounting for factors like age, sex, genetics, and seasonal variations, these approaches could advance personalized technologies for health promotion and longevity.

Conflict of interest

The authors declare no conflict of interest.

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