Modern Health Science; Vol. 8, No. 3; 2025
ISSN 2576-7291 E-ISSN 2576-7305
https://doi.org/10.30560/mhs.v8n3p16

The Modulatory Effects of Tai Chi on the Circadian Rhythms and Sleep Quality of Seafarers in Different Navigational Regions

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Received: July 6, 2025; Accepted: July 18, 2025; Published: July 22, 2025

Abstract

The circadian rhythm and sleep quality of seafarers are critical for their health and maritime safety; however, both are highly susceptible to disruption by environmental factors specific to different navigational regions. In particular, trans-meridian (east-west) voyages involving rapid time-zone crossings, and high-latitude (north-south) voyages encountering polar day/night phenomena, can severely disrupt the human circadian system. This study aims to investigate the potential modulatory effects of Tai Chi, as a non-pharmacological and easily implementable mind-body intervention, on the circadian rhythms and sleep quality of seafarers under different navigational conditions and to explore its differential mechanisms. This paper first systematically analyzes the core challenges to circadian rhythms posed by two typical navigational regions: the former leading to phase desynchronization between the internal clock and the external environment, and the latter causing a deficiency or disturbance of the primary zeitgeber (light). Subsequently, the paper reviews the scientific evidence for Tai Chi's role in regulating the autonomic nervous system, optimizing neuroendocrine rhythms, and improving sleep architecture. Based on this, a core theoretical model is proposed, positing that Tai Chi may act as a potent "non-photic zeitgeber". Through regular, daily practice at a fixed time, it can provide a stable and predictable synchronizing signal to the seafarer's internal biological clock. We further hypothesize that Tai Chi's mechanism of action is context-dependent: during trans-meridian voyages, it primarily serves as a rhythmic anchor to accelerate phase re-entrainment and combat jet lag; during high-latitude voyages, it functions to substitute and enhance a weak or absent light signal, helping to maintain the stability of endogenous rhythms. To validate this model, a 2x2 factorial designed randomized controlled trial is proposed to prospectively compare changes in circadian rhythms (measured by actigraphy and salivary hormones) and subjective sleep quality between a Tai Chi intervention group and a control group across the two different navigational regions. This research not only aims to provide an innovative and scientific intervention for the sleep and rhythm problems faced by seafarers in extreme environments but also seeks to deepen the understanding of mind-body exercise as a form of behavioral chronotherapy, thereby opening new avenues for safeguarding the health and safety of special occupational populations.

Keywords: circadian rhythm, sleep quality, Tai Chi, seafarers, navigational regions

1. Introduction

The shipping industry is the lifeblood of global trade, and seafarers are the most active and critical cells within this lifeline. However, this population faces a perennially overlooked health adversary: circadian rhythm disruption. Nearly all physiological functions in the human body—from the sleep-wake cycle, body temperature fluctuations, and hormone secretion to cognitive performance—are precisely regulated by an internal biological clock (located primarily in the suprachiasmatic nucleus (SCN) of the hypothalamus), which generates a rhythm of approximately 24 hours.[1] This internal clock relies on external environmental cues, especially light, for daily calibration to remain synchronized with the Earth's rotation. However, the operational environment of seafarers, particularly their trans-regional mobility, poses an unprecedented challenge to this sophisticated system.[2]

Different navigational regions present distinct types of rhythmic interference. When a vessel sails across longitudes on an east-west route, seafarers traverse multiple time zones in a short period. Their internal clock cannot rapidly adapt to the drastic changes in the external light-dark cycle, leading to a desynchronization between internal rhythms and the external environment. This results in symptoms similar to aeronautical "jet lag", including difficulty falling asleep, daytime sleepiness, digestive issues, and mood swings. Conversely, when a vessel sails

across latitudes on a north-south route, especially when entering polar or near-polar regions, seafarers face abnormal photoperiods such as the "polar day" (up to 24 hours of light) or "polar night" (up to 24 hours of darkness).[3] In such conditions, the primary zeitgeber—the light signal—becomes weak, chaotic, or even absent. This deprives the internal clock of its compass for calibration, leading to rhythm drift and reduced amplitude, which likewise cause severe sleep and health problems.

These rhythm disruptions, dictated by navigational region, not only seriously impair seafarers' sleep quality and long-term health (increasing the risk of cardiovascular disease and metabolic syndrome) but also directly threaten maritime safety.[4] Fatigue, decreased vigilance, and impaired judgment are significant human factors contributing to maritime accidents. Current interventions for seafarers' sleep problems often focus on pharmaceuticals or light therapy. However, drugs have side effects and potential for dependency, while the application of light therapy devices onboard is limited. Therefore, there is a significant practical need to find a safe, effective, low-cost, and easily implementable non-pharmacological intervention.

Tai Chi, a traditional mind-body practice integrating slow movements, deep breathing, and mental focus, has been shown to be effective in improving sleep quality in the general population and in patients with chronic insomnia. Its minimal space and equipment requirements make it highly suitable for seafarers to practice in confined spaces. However, no study has yet systematically investigated the direct modulatory effects of Tai Chi on circadian rhythms, nor has any research examined whether its effectiveness varies as a function of the critical environmental variable of navigational region.[5]

The novelty of this paper lies in its pioneering introduction of a chronobiological perspective to the study of mind-body interventions for seafarers. It poses a core scientific question: Can Tai Chi act as a behavioral zeitgeber to help seafarers better maintain their circadian rhythm stability and improve sleep quality under the challenges of different navigational regions? Do its mechanisms of action differ between trans-meridian and abnormal photoperiod voyages? This study aims to construct a theoretical framework and propose a corresponding experimental design to systematically answer these questions.[6] We hypothesize that Tai Chi, through its multi-dimensional mind-body regulation, can provide a powerful non-photic synchronizing signal to the seafarer's biological clock, thereby serving as a positive rhythm stabilizer under different types of navigational challenges.[7]

2. Theoretical Foundation and Literature Review

2.1 Mechanisms of Navigational Challenges to Circadian Rhythms and Sleep

2.1.1 Trans-meridian Navigation: Phase Desynchronization

The human internal biological clock has a certain inertia, capable of only a limited phase advance or delay each day (typically 1-2 hours). When a ship travels rapidly eastward (requiring a phase advance, e.g., sleeping earlier) or westward (requiring a phase delay, e.g., sleeping later), the rapid change in time zones exceeds the natural adjustment capacity of the biological clock. This leads to a temporary decoupling between endogenous rhythms (e.g., the peak of melatonin secretion, the nadir of core body temperature) and the exogenous environmental cycle (the new light-dark cycle and work-rest schedule).[8] This desynchronization is the physiological basis of jet lag, and the speed of recovery depends on the number of time zones crossed and individual adaptability. For seafarers, continuous and repeated trans-meridian voyages can lead to chronic circadian disruption.

2.1.2 High-latitude Navigation: Zeitgeber Deficiency

Light is the most potent zeitgeber (from German, meaning "time-giver") for regulating the SCN.[9] Morning light suppresses melatonin secretion and resets the biological clock, which is key to maintaining a 24-hour rhythm. In the summer at high latitudes (polar day), continuous light exposure persistently suppresses melatonin secretion, making sleep onset difficult and potentially reducing the amplitude (i.e., the day-night difference) of circadian rhythms. In the winter (polar night), the lack of a sufficiently strong daylight signal means the biological clock cannot receive a clear morning cue, which can lead to free-running—a state where the rhythm's period deviates from 24 hours. This results in irregular sleep timing and an overall tendency towards chaotic rhythms.[10]

2.2 Potential Mechanisms of Tai Chi in Regulating Sleep and Circadian Rhythms

Although direct research on Tai Chi's effect on circadian rhythms is scarce, its impact on sleep-related physiological systems is well-documented, indirectly pointing to its potential for rhythm regulation.

2.2.1 Regulation of the Autonomic Nervous System (ANS)

The initiation and maintenance of sleep depend on the dominant activity of the parasympathetic nervous system. The deep, slow breathing and relaxation techniques in Tai Chi have been shown to significantly increase heart rate variability (HRV) and enhance vagal tone.[11] This promotes a shift from a sympathetic-dominant "fight or flight"

state to a parasympathetic-dominant "rest and digest" state. This state transition is a prerequisite for sleep onset and can help alleviate sleep difficulties caused by stress or rhythm disruption.

2.2.2 Optimization of the Neuroendocrine System

Cortisol Rhythm: Cortisol, a stress hormone, has a distinct diurnal rhythm (high in the morning, low at night). Chronic stress and circadian disruption can flatten this rhythm, leading to elevated nocturnal cortisol levels that interfere with sleep. Studies indicate that mind-body practices like Tai Chi can lower overall cortisol levels and may help restore its normal diurnal pattern.[12]

Melatonin Secretion: Melatonin is a key hormone regulating sleep, and its secretion is strictly controlled by the SCN, peaking in darkness. While there is no direct evidence that Tai Chi increases melatonin secretion, by lowering nocturnal cortisol levels and promoting relaxation, it may create a more favorable physiological environment for normal melatonin release.

2.2.3 Improvement of Sleep Architecture

Research has found that long-term Tai Chi practice can increase total sleep time, reduce sleep onset latency, and potentially increase the proportion of deep sleep (slow-wave sleep). Deep sleep is crucial for physical restoration and memory consolidation, and improving its quality can help counteract the daytime functional impairments caused by circadian disruption.

2.3 Theoretical Innovation: Tai Chi as a "Non-Photic Zeitgeber"

Besides light, regularly scheduled social activities, meal times, and physical exercise are also considered secondary, non-photic zeitgebers, which can also influence the biological clock. The core theoretical hypothesis of this study is: Daily Tai Chi practice performed at a fixed time can serve as a potent and reliable non-photic zeitgeber, providing a crucial synchronizing signal to the seafarer's biological clock.[13]

This signal is transmitted to the SCN via multiple pathways: Body Temperature Rhythm: Regular exercise induces rhythmic fluctuations in body temperature, which is an important signal influencing the SCN; Neurotransmitter Changes: Exercise can cause rhythmic changes in brain neurotransmitters like serotonin, which are also involved in the regulation of the biological clock; Behavior and Arousal: A daily, timed, conscious mind-body activity itself constitutes a strong behavioral anchor for the sleep-wake cycle.[14] Based on this, we propose a differential mechanism hypothesis for different navigational regions.

3. Differential Mechanism Model and Research Hypotheses

We construct a differential action model to illustrate the different roles Tai Chi may play in the two navigational regions.

Model 1: In Trans-meridian Regions — The Rhythmic Anchor

Core Problem: Phase desynchronization. The biological clock needs to catch up to the new time zone as quickly as possible.

Role of Tai Chi: Daily Tai Chi practice at a fixed time (e.g., at a specific time referenced to the port of departure or GMT) acts like a temporal anchor cast in a drifting sea. This punctual daily signal, which includes physiological arousal and temperature changes, provides the SCN with an extremely stable reference point in addition to light, helping to accelerate the process of phase re-entrainment. It can help the body adapt to the new schedule more quickly, thereby shortening the duration of jet lag and improving sleep quality during the transition period.

Model 2: In High-latitude Regions — The Signal Substitute/Enhancer

Core Problem: The primary zeitgeber (light) signal is weak or absent. The biological clock is at risk of free-running.

Role of Tai Chi: In an environment lacking reliable light cues, the importance of this potent non-photic zeitgeber is magnified. It is no longer auxiliary to light but rather substitutes for or greatly enhances the weak environmental signal. Daily timed practice can help force the body to maintain a rhythm close to 24 hours, preventing the biological clock from drifting. It provides the body with an artificial sunrise, helping to maintain the rhythmicity of wakefulness-sleep, body temperature, and hormone secretion.

Based on the above models, the following hypotheses are proposed:

H1 (Main Effect Hypothesis): Regardless of the navigational region, compared to the control group, seafarers receiving the Tai Chi intervention will show better maintenance of circadian rhythm stability (e.g., rhythm amplitude, intradaily variability) and significantly improved sleep quality (measured by actigraphy and subjective scales).

H2 (Interaction Effect Hypothesis): The specific pattern of circadian modulation by Tai Chi will differ between navigational regions. We predict that:

H2a: In the trans-meridian group, the Tai Chi intervention will primarily manifest as faster phase adaptation (i.e., the acrophase of the activity rhythm will align more quickly with the new schedule).

H2b: In the high-latitude group, the Tai Chi intervention will primarily manifest as more stable rhythm amplitude and stronger 24-hour periodicity (i.e., preventing rhythm decay and drift).

4. Research Design and Methods

4.1 Study Design

This study will employ a 2 (Intervention: Tai Chi vs. Control) × 2 (Navigational Region: Trans-meridian vs. High-latitude) Factorial Design. This is a prospective randomized controlled trial that can simultaneously test the main effect of the intervention and the interaction effect between the intervention and environmental factors.

4.2 Participants

We plan to recruit 120 healthy male seafarers from vessels scheduled for trans-meridian routes (e.g., Asia-Europe) and high-latitude routes (e.g., Arctic passages or near-Antarctic routes).

Random Allocation: Within each navigational region, seafarers will be randomly assigned in a 1:1 ratio to the Tai Chi group (n=30) or the control group (n=30), resulting in four experimental cells.

Inclusion/Exclusion Criteria: Similar to previous studies, ensuring participants have no prior Tai Chi experience, no serious physical or mental illnesses, and provide voluntary consent.

4.3 Intervention Protocol

Tai Chi Intervention Group (n=60): During the voyage, participants will engage in 30 minutes of a simplified 24-form Tai Chi routine at a fixed time each day (e.g., uniformly scheduled at 10:00 AM local ship time), guided by video tutorials. The fixed timing is central to this study's design and key to achieving the zeitgeber effect.

Control Group (n=60): Will be provided with health education materials to read for an equivalent amount of time or will perform general stretching exercises, but without a prescribed fixed time, to control for non-specific effects.

4.4 Measurement Instruments (Core Section)

To objectively assess circadian rhythms, this study will use multi-dimensional measures:

Primary Outcome Measures (Objective Circadian Rhythms):

Actigraphy: All participants will wear a wrist-worn actigraph (e.g., Actiwatch) continuously throughout the voyage. This device records physical activity and light exposure, allowing for the analysis of:

Sleep Parameters: Total Sleep Time, Sleep Onset Latency, Sleep Efficiency, Wake After Sleep Onset.

Circadian Rhythm Parameters: Non-parametric analysis (e.g., Intradaily Variability (IV), Interdaily Stability (IS)) and parametric Cosinor analysis to derive the rhythm's Acrophase (timing of the peak), Amplitude (strength of the rhythm), and MESOR (rhythm-adjusted mean). These are the gold-standard metrics for rhythm phase, strength, and stability.

Salivary Hormone Rhythms: During specific 24-hour periods before, during, and after the voyage, saliva samples will be collected every 4 hours to measure the concentrations of cortisol and the melatonin metabolite (aMT6s) to plot their diurnal rhythm curves.

Secondary Outcome Measures (Subjective Experience):

Pittsburgh Sleep Quality Index (PSQI): To assess subjective sleep quality.

Epworth Sleepiness Scale (ESS): To assess daytime sleepiness.

Morningness-Eveningness Questionnaire (MEQ): To assess individual chronotype preference.

4.5 Data Collection and Analysis

Data Collection: All data will be collected at three time points: one week before the voyage (baseline), mid-voyage (e.g., week 4), and one week before the end of the voyage (endpoint).

Data Analysis:

A 2×2 Repeated Measures ANOVA or a Mixed-Effects Model will be used for the primary analysis. Intervention (Tai Chi/Control) and Navigational Region (Trans-meridian/High-latitude) will be the between-subjects factors, and Time (Baseline/Midpoint/Endpoint) will be the within-subjects factor.

The primary focus will be on the three-way "Intervention × Region × Time" interaction effect. A significant effect would indicate that the effect of Tai Chi indeed varies depending on the navigational region and time.

This will be followed by simple effects and simple interaction analyses to test the specific hypotheses H2a and H2b. For example, within the trans-meridian group, the rate of phase shift will be compared between the Tai Chi and control groups; within the high-latitude group, the change in rhythm amplitude will be compared.

5. Expected Results and Discussion

Expected Results:

We expect to observe a significant three-way interaction effect.

Specifically, during trans-meridian voyages, the acrophase of the activity rhythm in the Tai Chi group will adapt more quickly to the new time zone compared to the control group.

During high-latitude voyages, the rhythm amplitude in the Tai Chi group will be better maintained, showing less decay than in the control group.

In both navigational regions, the Tai Chi group will show significantly better subjective sleep quality (PSQI scores) and lower daytime sleepiness (ESS scores) compared to the control group.

Theoretical Contributions and Practical Implications:

Theoretically, if confirmed, these results would provide the first direct, objective physiological evidence for "Tai Chi as a non-photic zeitgeber". This would uncover the differential mechanisms by which mind-body exercise regulates the biological clock, contributing new knowledge to the intersection of chronobiology and exercise medicine.

Practically, the findings would offer a strong scientific basis for shipping companies to develop health and safety strategies for their crews. A simple yet effective chronotherapy could be promoted: encourage seafarers to practice Tai Chi at a fixed time each day, regardless of the ship's time zone. This method requires no extra cost but could become a powerful tool against jet lag and extreme light environments, holding immeasurable value for improving seafarer health and ensuring maritime safety.

6. Conclusion

The stability of circadian rhythms is the cornerstone of seafarer health and safety. Through innovative theoretical construction and rigorous experimental design, this study aims to systematically explore the unique role of the ancient wisdom of Tai Chi in addressing the distinct circadian challenges posed by modern seafaring. By positioning Tai Chi as a non-photic zeitgeber and differentiating its roles in rhythmic anchoring and signal substitution, this research not only promises to provide an effective new health intervention for seafarers but will also deepen our understanding of how human behavior interacts with the internal biological clock. Ultimately, the findings of this study could transcend the maritime domain, offering insights for all shift workers and trans-meridian travelers who face the challenge of circadian rhythm disruption.

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