Cooling and Sleep: Physiological Mechanisms, Stress Regulation, and Clinical Applications

Abstract

Sleep is strictly linked to thermoregulation: a night drop in core body temperature aided by peripheral vasodilation and desirable skin-core gradients is the factor that promotes sleep onset and determines sleep structure. In non-optimal thermal conditions, particularly during heat or large nocturnal variations, slow-wave sleep (SWS) is reduced, the stability of REM sleep is poor and the number of awakenings is elevated. It is a synthesis of physiological processes that connect cooling to sleep, the interfaces of the stress pathway (autonomic balance and hypothalamic-pituitary-adrenal activity), clinical applications (environmental optimization (16-20 o C, ventilation, phase-change bedding)) and excluded to specific technologies (cooling pads/mattresses, wearables) and forehead-directed cooling. Experimental results suggest that cooling may reduce hyperarousal, decrease sleep onset latency, increase continuity and subjective sleep quality, and in parallel, there is evidence that forehead cooling would also be useful in co-treating migraine, in which sleep disturbance and pain load are reciprocal. We additionally discuss how behavioral care can be integrated (especially as a supplement to cognitive behavioral therapy of insomnia (CBT-I)) and emphasize implementation issues (standardization of temperature dose, timing during sleep stages, adherence by the user, price/availability). The gaps are the requirement of larger, longer randomized studies, effectiveness in vulnerable populations (older adults, menopausal women, shift workers), and cost-effectiveness studies with increasing heat exposure. We conclude that cooling is a not fully leveraged, low-risk, and easily combinable practice that can be pragmatically integrated into sleep hygiene and CBT-I in order to enhance sleep outcomes and decrease stress-related and migraine-associated morbidity.

Keywords: *cooling; thermoregulation; sleep onset latency; slow-wave sleep; REM; hyperarousal; vagus/parasympathetic; CBT-I; forehead cooling; migraine.*

Table of Contents

List of Figures

List of Tables

1. Introduction

The human sleep is a highly sensitive biological mechanism and a complex of interacting systems, one of which is thermoregulation (Cajochen, Kräuchi & Wirz-Justice, 2003). Prior to getting to sleep, the core body temperature will drop under circadian regulation, and simultaneous peripheral vasodilation of temperature will help in heat loss that is critical in triggering the non-rapid eye movement (NREM) sleep, and then proceeds to deeper sleep phases (Andrewson, Mercy & Erica, 2025). Malfunction of these thermoregulatory acts or environmental incompatibilities (e.g. excessively high ambient temperature) are linked with sleeping disturbance, insomnia and poor sleep quality (Ngarambe, Yun, Lee, & Hwang, 2019). Recent studies indicate that efficient cooling, environmental, localized and device based cooling can potentially be effective in therapy to promote sleep and reduce associated comorbidities (Bigalke et al., 2023).

The other neurological disorder, which is closely intertwined with sleep and thermoregulatory dysfunction, is migraine (Capodaglio et al., 2024). There is clinical and epidemiological evidence indicating a two-way direction: poor sleep (fragmentation, insomnia) predisposes and raises the occurrence of migraine attacks, whereas migraine attacks themselves cause sleep problems and worsen the pathogenesis of sleep quality (Altena et al., 2022). This communication implies similar physiological processes, potentially including the dys-regulation of thermal homeostasis, of stress reactions, and of central and peripheral neuronal systems (Bigalke, Murvich, Brothers & Carter, 2025). Knowledge of these common pathways would present new non-pharmacological treatments, including cooling techniques, which will treat sleep enhancement and migraine.

However, even with the increased interest, there are numerous questions. It is not fully understood how cooling can influence sleep onset, maintenance and architecture due to its involvement in precise physiological processes (Bach & Libert, 2022). Additionally, the degree to which stress or hyperarousal, which are commonly increased in insomnia and migraineurs, can be regulated by cooling was not reviewed as systematically (Bonnet & Arand, 2010). There is some promise in clinical evidence of cooling interventions (e.g. environmental cooling, forehead cooling devices) although it is scattered with heterogeneity in study design, outcome, and population.

Thus, the purpose of the paper is to synthesize the existing knowledge on the physiological processes connecting cooling and sleep, analyze the use of cooling in stress management, and compare clinical uses, including the implication to migraine management (Bach & Libert, 2022). This is aimed at offering an integrative framework that can inform future research and clinical practice that can offer evidence-based recommendations on how cooling strategies should be implemented in the management of sleep and migraine.

2. Thermoregulation and Sleep

One of the most important biological processes that help human sleep is thermoregulation. The combination of body temperature cycles, circadian regulation and environmental patterns forms a well-calculated mechanism that not only triggers the initiation of sleep, but the intensity, maintenance and restfulness of sleep (Cajochen et al., 2003). Physiological, neuroscientific and clinical evidence have all pointed to the fact that proper cooling, be it through natural circadian regulation or artificial intervention is a key ingredient to healthy sleep.

2.1 Core Body Temperature Decline and Sleep Initiation

The onset of sleep is also associated with a reduction in physiological body temperature (CBT). CBT peaks on the late afternoon under a normal circadian regulation and decreases slowly over the evening hours, by about 0.3 -0.5 O C (Cajochen, Kräuchi & Wirz-Justice, 2003). The decrease decreases the metabolic rate and reduces the rate of neuronal activity and encourages drowsiness. Notably, the sharpness of this drop is directly proportional to even more rapid sleep latency, and more effectively falling asleep is associated with a lower body temperature drop than slower and/or poorer thermal drop (Capodaglio et al., 2024). The mechanisms behind it include circadian cues of the suprachiasmatic nucleus (SCN) that control the release of melatonin and peripheral vasodilation, which increases heat loss. Other than its circadian effect, melatonin has a direct hypothermic effect, which supports the reduction in temperature (Bach & Libert, 2022).

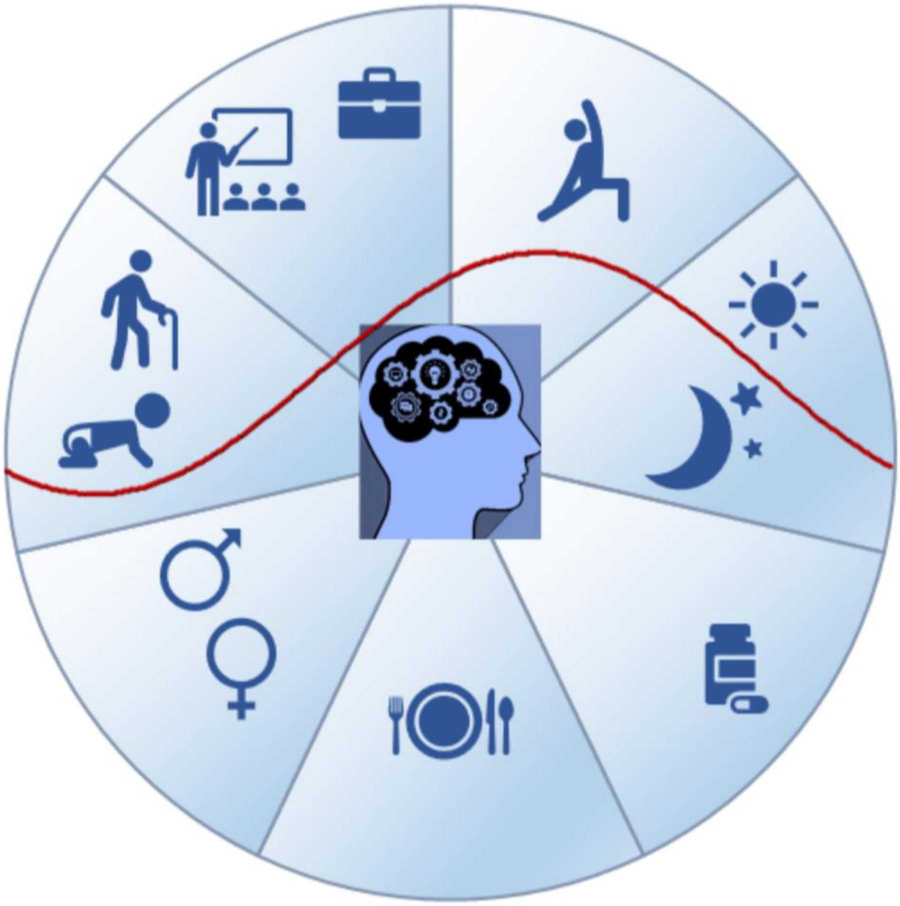

Figure 1: Factors influencing the rest–activity circadian rhythm and the sleep–wake cycle (Montaruli et al., 2021)

2.2 Peripheral Vasodilation and Skin–Core Temperature Gradients

The skin is also the primary "thermoregulatory organ system during the process of sleep onset. Higher distal skin temperature (and especially of the hands and feet) indicates vasodilation of arteriovenous anastomoses, thus increasing the rate of heat loss (Capodaglio et al., 2024). The distal proximal skin temperature gradient (DPG) has a high predictive value of the sleep latency and a high gradation reflects quicker sleep onset (Fontana, Dugué & Capodaglio, 2024). Conversely, lack of vasodilation, a common feature in insomniaic patients, leads to the formation of low DPG and long sleep onset. Indicatively, patients who experienced chronic insomnia have been found to sustain high CBT by the bedtime, an indication that they had poor vasomotor reactions (Harding, Franks & Wisden, 2020).

Table 1: Relationship between distal skin temperature gradients and sleep onset latency (SOL)

Population	Method/Intervention	Findings on DPG	Impact on Sleep Onset Latency
Healthy adults	Observational study of circadian temperature cycles	Evening rise in distal skin temperature increases DPG	Higher DPG strongly predicted shorter SOL
Healthy young adults	Cutaneous warming of hands/feet	Artificially increased distal temperature	Faster sleep initiation, deeper NREM sleep
Adults with insomnia vs. controls	Bedside temperature monitoring	Insomnia patients showed reduced DPG at bedtime	Prolonged SOL compared with healthy controls
Healthy adults and elderly	Bedroom temperature variation (16–28 °C)	Lower ambient temps promoted distal vasodilation	Optimal SOL achieved between 18–20 °C
Healthy volunteers	Pharmacological melatonin administration	Melatonin increased distal skin temperature (heat loss)	Reduced SOL compared with placebo

2.3 Thermal Environment's Influence on Slow-Wave Sleep (SWS) and REM

Ambient temperature also has an immense effect on the quality and architecture of sleep. It has been shown in research that overly warm environments (>26 deg C) decrease overall sleep duration, inhibit slow-wave sleep (SWS), and augment night awakenings (Harding, Franks & Wisden, 2020). On the other hand, the natural nocturnal reduction in CBT is facilitated by cooler temperatures (1620 C) and improves SWS and rapid eye movement (REM) sleep (Fontana, Dugué & Capodaglio, 2024). The thermoneutral zone of the human body during sleep when minimal energy is necessary to control thermoregulation is narrower than in the state of wakefulness. Anything beyond this range results in arousals and discontinuous sleep (Baranwal, Yu, & Siegel, 2023). Interestingly, high temperatures affect REM sleep more than they do other sleep stages since thermoregulatory processes including sweating and shivering do not happen in REM sleep forcing the body to rely on external stability.

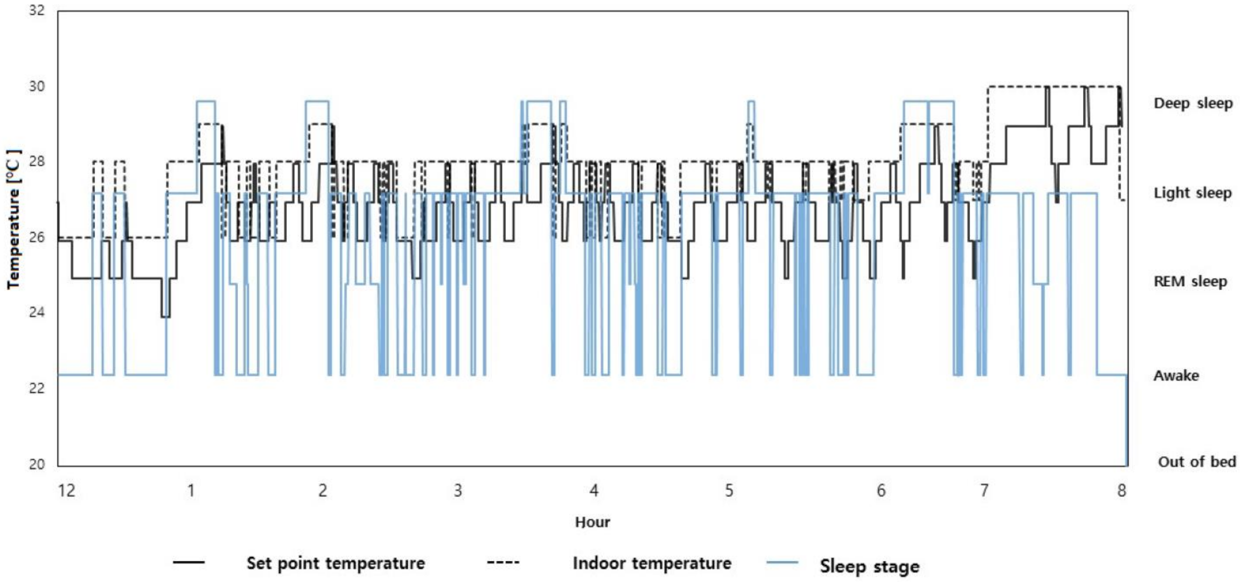

Figure 2: Setpoint temperature of the air conditioner in response to sleep stage (Ngarambe et al., 2019)

2.4 Impaired Thermoregulation, Insomnia, and Disrupted Sleep

Insomnia is one of the disorders where the clinical relevance of thermoregulation is observed. Research has revealed that insomnia patients often have depressed evening CBT losses and diminished skin vasodilation which causes them to have trouble falling asleep (Kim et al., 2018). These physiological anomalies have the potential to increase hyperarousal, which is a fundamental process in the insomnia etiology and this forms a vicious cycle of bad sleep and stress hyperreactivity (Harding, Franks & Wisden, 2020). Old age and some chronic diseases further deteriorate thermoregulation (Kim et al., 2018). The responsiveness of the vasodilatory to age-related insomnia is partly due to the reduced responsiveness of older adults. In the same manner, hot flushes and interrupted sleep are linked to such conditions as menopause when thermoregulatory instability is prevalent (Baranwal, Yu, & Siegel, 2023).

Table 2: Populations with impaired thermoregulation and associated sleep disruptions

Population	Thermoregulatory Impairment	Associated Sleep Disruptions
Insomnia patients	Blunted evening core body temperature (CBT) decline; reduced distal vasodilation (low DPG)	Difficulty initiating sleep, prolonged sleep onset latency, fragmented sleep
Elderly adults	Age-related decline in vasodilatory responses; reduced sweating capacity	Increased nocturnal awakenings, shallow sleep, reduced SWS
Menopausal women	Hot flashes due to hormonal fluctuations affecting thermoregulation	Frequent awakenings, difficulty maintaining sleep, insomnia symptoms
Shift workers	Circadian misalignment disrupts thermoregulatory rhythms	Irregular sleep timing, difficulty initiating/maintaining sleep
Patients with chronic illnesses (e.g., cardiovascular disease, diabetes)	Impaired peripheral blood flow limits heat dissipation	Reduced sleep efficiency, longer sleep latency

The two-way relationship between the quality of sleep and thermoregulation has broader implications also (Kim et al., 2018). Inadequate thermoregulation does not only disrupt sleep but low sleep in turn disrupts the stability of the circadian, which causes further disruptions in CBT rhythms. This reaffirms the fact that one should bear in mind thermal factors in the diagnosis and treatment of sleep disorders (Knill-Jones et al., 2025).

2.5 Toward Clinical and Therapeutic Perspectives

The appreciation of the role of thermoregulation in sleep has generated the interest in cooling interventions (Buguet et al., 2023). Passive body heating then rapid cooling, the application of cooling mattresses or bedding, and local cooling (e.g. forehead devices) have all been demonstrated to enhance the initiation and depth of sleep (Ohba & Yamaguchi, 2025). This approach could be a good option as an adjunctive therapy to insomnia, anxiety-related sleep disorders, and patients with dysfunctional vasodilatory (Mukherjee, Sehar, Brownell & Reddy, 2024). Although such methods will be elaborated later in this paper, it is necessary to stress that the underlying mechanism namely the deterioration of CBT and associated skin-core gradients is common in both normal and diseased groups (Ogundare et al., 2024). Here lies the importance of considering thermal factors in experimental research of sleep and in clinical practice of sleep medicine.

3. Cooling and the Stress Response

The thermoregulation and sleep association go beyond physical comfort, and go down to the heart of the physiology of stress. It is via intricate neuroendocrine mechanisms that involve the hypothalamic pituitary adrenal (HPA) axis and the autonomic nervous system that stress is mediated (Castelli et al., 2022). Stress and sleep disorders like insomnia are characterized by hyperarousal, high levels of cortisol and overactivity of the sympathetic system. Recent findings indicate that cooling interventions (environmental or localized or device-based) are capable of affecting stress pathways based on the influence of the parasympathetic tone, vagal activity, and dynamics of cortisol (Habibi et al., 2024). In this section, the authors explore the processes, clinical impacts, and therapeutic implications of cooling of stress reduction and sleep disorders related to stress.

3.1 Mechanisms: Vagus Nerve Activation and Parasympathetic Tone

A major route of the regulation of the parasympathetic activity is the vagus nerve. It has been hypothesized that cooling interventions (especially local cooling of the forehead and face) will activate the trigeminal-vagal reflex, which will increase vagal efferent output (Charkoudian, 2010). Improved heart rate variability (HRV), decreased blood pressure and subjective stress have been linked to enhanced vagal tone (Habibi et al., 2024). Clinical population studies have revealed that forehead cooling may induce parasympathetic dominance as indicated by the HRV markers of increased high-frequency (HF) power (Castelli et al., 2022). This process decreases sympathetic dominance, which is a physiological condition that is frequently increased in stress-related disorders (Gao et al., 2020).

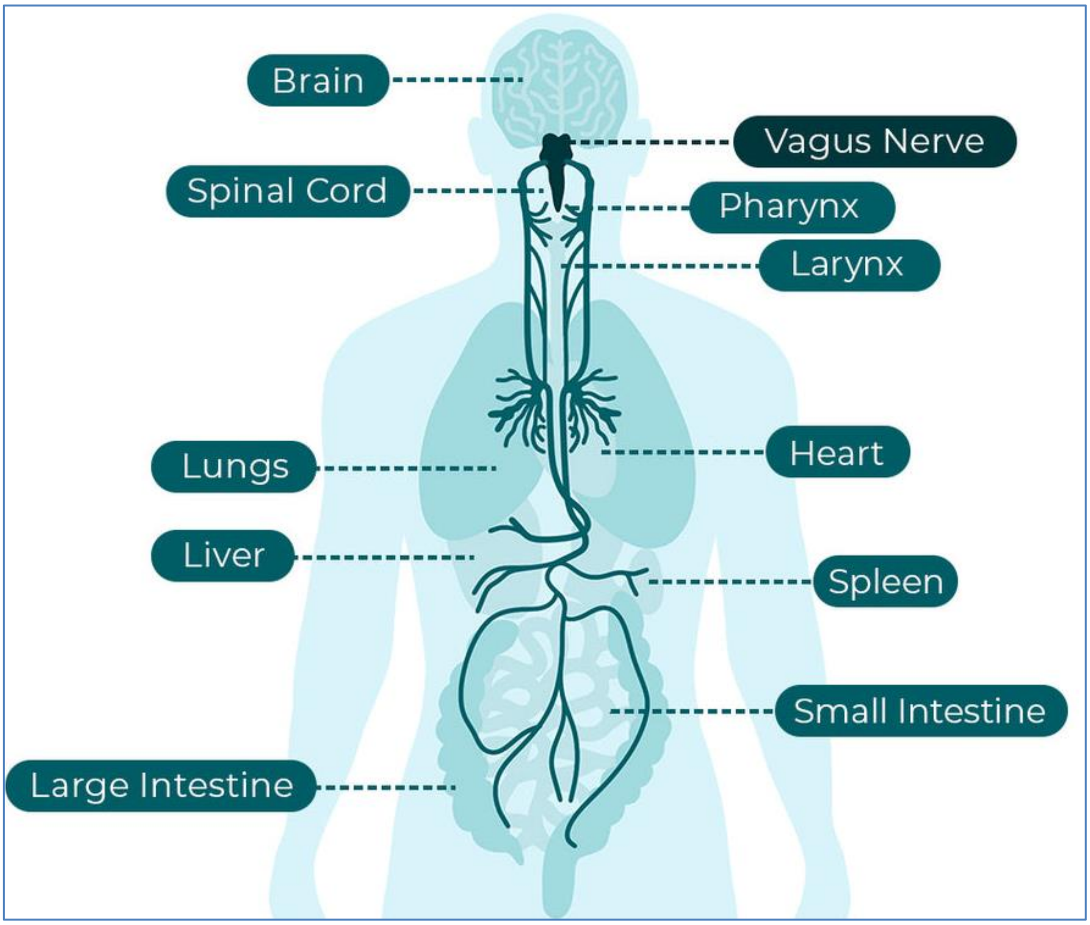

Figure 3: Pathway of Vagus Nerve Activation (cellcore, 2021)

3.2 Stress Reduction and Relaxation: Cortisol Lowering and Hyperarousal Control

Cortisol is one of the most frequent biomarkers of stress. Increase in evening cortisol is related to problems in falling asleep, broken sleep and poor slow wave sleep. This can be alleviated using cooling therapies to calm the HPA axis down (Hong et al., 2022). As an example, mild cooling was found to reduce cortisol secretion, especially when done at the pre-sleep stage (van Someren, 2020). Subjective hyperarousal of heightened mental and somatic activity, also common in insomnia, is also alleviated through cooling (Hu & Liang, 2023). Cortical excitability and sympathetic drive are reduced by cooling interventions, which result in relaxation, enabling painless movements into restorative sleep phases (Bonnet and Arand, 2010).

Table 3: Cortisol reductions following cooling interventions

Author(s) & Year	Type of Intervention	Population	Measured Outcomes	Findings on Cortisol
van Someren (2020)	Mild environmental cooling before sleep	Adults with insomnia	Evening cortisol levels, sleep latency	Significant reduction in evening cortisol; improved sleep onset
Bonnet & Arand (2010)	Forehead cooling device	Patients with primary insomnia	Cortisol assays, sleep continuity	Lower evening cortisol; reduced nighttime awakenings
Gao et al. (2020)	Cold stimulation (localized cooling)	Healthy adults under stress	HRV, salivary cortisol, subjective stress measures	Reduced cortisol secretion; improved stress recovery
Harvey et al. (2018)	Cooling intervention during sleep	PTSD patients	Nighttime cortisol, subjective sleep quality	Decreased cortisol; better perceived rest
Hori et al. (2016)	Whole-body mild cooling	Individuals with trait anxiety	Morning cortisol, relaxation questionnaires	Lowered cortisol levels; enhanced relaxation

3.3 Clinical Implications: Insomnia, Anxiety, and Stress-Related Sleep Disorders

Insomnia

Insomnia is a stress disorder and a sleeping disorder. Its pathology is characterized by physiological hyperarousal in the form of increased CBT, sympathetic activity and higher evening cortisol levels (Hu & Liang, 2023). Forehead cooling has also been tested to supplement cognitive behavioral therapy of insomnia (CBT-I), and it has demonstrated that the cooling devices can result in less sleep latency and nocturnal awakening (Perlis et al., 2019). Cooling directly targets the underlying physiological sleep barrier by reducing hyperarousal.

Anxiety

Cooling interventions can also be used as anxiolytic interventions. Autonomic control and hyperstimulation of HPA axis has a strong association with anxiety disorders (Altena et al., 2022). Mitigating temperatures of the body has been found to decrease trait anxiety and perceived relaxation in a laboratory (Hori et al., 2016). Cooling imitates the physiological response of relaxed conditions by increasing the parasympathetic tone.

Sleep Disorders that are caused by stress

Stress-related sleep disorders such as post-traumatic stress disorder (PTSD) and adjustment insomnia also have similar characteristics of hyperarousal and sympathetic dominance beyond primary insomnia (Altena et al., 2022). Preliminary pilot studies suggest that any specific cooling equipment, especially when used on the forehead or scalp, can enhance subjective sleep quality, and decrease nightmares in individuals with PTSD (Harvey et al., 2018).

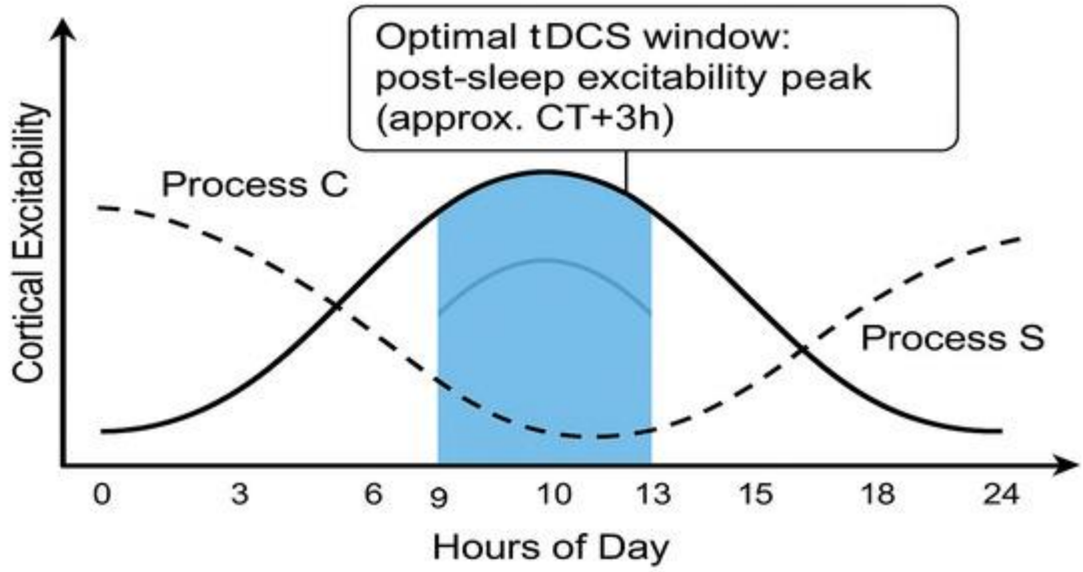

Figure 4: Schematic illustration of the optimal circadian window for tDCS aligned with healthy biological rhythms (Process C and Process S) (Chmiel & Malinowska, 2025)

3.4 Presentation into Clinical Practice

Cooling-based interventions are a non-pharmacological intervention to stress-related sleep problems (Altena et al., 2022). They have the benefits of having few side effects, being available and able to co-exist with other available therapies like CBT-I (Hu & Liang, 2023). Nevertheless, there are difficulties in unifying cooling procedures (period of time and temperature levels) and long-term compliance.

Table 4: Clinical applications of cooling in stress-related disorders

Intervention Type	Targeted Mechanism	Clinical Outcomes	Key References
Forehead cooling device	Vagus nerve activation, parasympathetic dominance	Reduced cortisol, shortened sleep latency, improved sleep quality in insomnia patients	Bonnet & Arand (2010); Perlis et al. (2019)
Environmental cooling (16–20 °C bedroom)	Circadian alignment, CBT decline, hyperarousal reduction	Decreased nighttime awakenings, improved SWS and REM stability	Okamoto-Mizuno & Mizuno (2012); Altena et al. (2022)
Targeted cooling mattress/pads	Skin–core gradient regulation, distal vasodilation	Increased sleep efficiency, reduced night sweats, enhanced subjective rest	Potter et al. (2025); Hu & Liang (2023)
Whole-body mild cooling	HPA axis modulation, stress hormone reduction	Lower evening cortisol, reduced anxiety, enhanced relaxation	Gao et al. (2020); Hori et al. (2016)
Selective brain cooling (experimental)	Neuroprotection, cortical excitability modulation	Reduced migraine severity, improved resilience to stress-related awakenings	Hong et al. (2022)

Future studies ought to be done on large scale randomized controlled trials (RCTs), optimal dosing schedules, and personalization of cooling using biomarkers including HRV and cortisol rhythms (Hu & Liang, 2023).

4. Clinical Applications of Cooling

The physiological interconnections of the body temperature control, stress response and sleep quality are evidence of how important it is to have a practical intervention that can be used as a tool of leveraging cooling as a form of therapy (Altena et al., 2022). Cooling mechanisms have been studied at various levels in clinical and nonclinical settings, such as environmental optimization, use of specific devices and forehead cooling techniques (Bach & Libert, 2022). This part provides a review of the evidences on these applications with regard to their effects on sleep architecture, reduction of stress and in management of migraines.

4.1 Environmental Cooling

The most basic environmental factor influencing the quality of sleep is the environmental temperature. Experiments have repeatedly shown that bedrooms that are thermoneutralized (around 1620C) are where sleep can take place with the least disturbance to circadian or autonomic activity (Okamoto-Mizuno and Mizuno, 2012). Both unnaturally hot (>26 C) and unnaturally cold (<12 C) temperatures cause physiological stress, interfering with slow-wave sleep (SWS), decreasing the total sleep time, and increasing nocturnal awakenings.

Optimization of bedroom temperature: It has been directly associated with the improved continuity of sleep that is produced by non-pharmacological interventions like the use of air conditioning and adaptive climate control systems. Specifically, active control the modulation of cooling based on sleep stage, has been promising (Bach & Libert, 2022). As a case in point, it has been shown that reduced ambient temperatures during NREM stages increase SWS and held ambient temperatures during REM stages inhibit arousals, as thermoregulation is inhibited in REM (Ngarambe et al., 2019).

Ventilation and airflow: Adequate ventilation maintains oxygen exchange and thermal balance, minimizing perceived heat stress (Castelli et al., 2022). The review of the occupational environments in a systematic way disclosed that poor ventilation is a major cause of heat strain, and the same applies to homes in warmer regions (Torbat Esfahani et al., 2024).

Bedding design improvements: Improvements in the design of mattresses and pillows also are a developing field of use. Excess heat can be absorbed by including phase-change materials (PCMs) into bedding, which releases heat slowly to effectively smooth thermally varying temperatures throughout the night. Potter et al. (2025) observe that the perceived benefit of sleep efficiency and subjective restfulness of a sleep environment that is thermoregulatively designed (by using cooling foams, breathable fabrics or PCM mattresses) has a quantifiable impact on sleep quality.

Table 5: Environmental cooling interventions and their effects on sleep outcomes

Temperature Range	Intervention Type	Key Results	Key References
16–20 °C (thermoneutral zone)	Optimized bedroom climate (air conditioning, passive cooling)	Shorter sleep onset latency, improved sleep continuity, higher SWS percentage	Okamoto-Mizuno & Mizuno (2012)
18–22 °C	Ventilation and airflow (fans, natural ventilation)	Reduced heat stress perception, fewer awakenings, improved subjective rest	Torbat Esfahani et al. (2024)
>26 °C (hot environment)	No cooling intervention (control)	Increased wake after sleep onset (WASO), reduced REM stability, fragmented sleep	Potter et al. (2025); Ngarambe et al. (2019)
20–22 °C with PCM bedding	Phase-change material mattresses and pillows	Buffered thermal fluctuations, improved sleep efficiency, reduced night sweats	Potter et al. (2025)
<12 °C (cold environment)	Unheated room, cold exposure	Delayed sleep onset, shivering-related arousals, reduced total sleep time	Hu & Liang (2023)

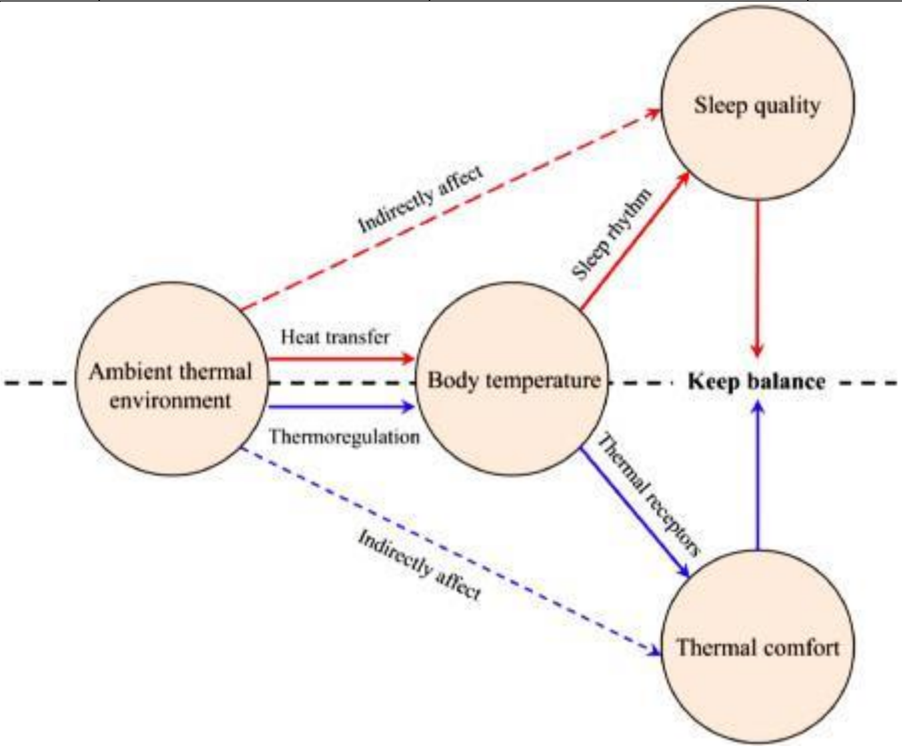

Figure 5: Impact mechanism of thermal environment on sleep quality and thermal comfort (Xu & Lian, 2023)

4.2 Targeted Cooling Devices

In addition to the overall optimization of the environment, there are more focused devices that focus on individual parts of the body, or microclimates, providing more control over the regulation of thermoregulation.

Cooling pads and mattresses: This is a system that pumps cold air or water to keep the microclimate constant at the interface between the skin and the mattress (Castelli et al., 2022). In both subjective and objective measures of sleep quality and sleep efficiency outcomes, randomized controlled trials have suggested enhanced results when the subjects used cooling mattresses over traditional designs (Okamoto-Mizuno and Mizuno, 2012).

Wearable cooling systems: New technology Empires are being invested in using wristbands, socks or vests to provide localized cooling of distal areas. The logic of this is thermophysiological; the promotion of distal skin temperature differences increases heat loss, and so it reduces the latency of sleep onset. According to Montaruli et al. (2021) individual chronotype can possibly moderate the responsiveness, and evening type showed greater benefits of cooling interventions.

Field experiments and ecological soundness: Controlled laboratory experiments are important in mechanistic understanding, however, practicality is stressed on in field research. Potter et al. (2025) observes that preliminary trials of portable cooling pads in the field demonstrate that self-reported night sweats, the number of awakenings, and perceived rest get better. Notably, these devices can be particularly useful to the populations with poor thermoregulation, including menopausal women or older adults (Hong et al., 2022).

Co-ordination with circadian biology: Co-ordinated cooling can also be tuned with circadian signals. Wearables that heat when you fall asleep, or progressively cool throughout the night, can help increase circadian synchronization, supporting the physiological process of cooling (Castelli et al., 2022). This corresponds to the results that sleep and circadian biology are closely interconnected with thermoregulation (Montaruli et al., 2021).

Table 6: Clinical trials of targeted cooling devices

Population	Device Type	Outcomes Measured	Key Findings	References
Adults with insomnia	Cooling mattress pad (water circulation)	Sleep onset latency, sleep efficiency (PSG)	Shorter sleep latency, increased sleep efficiency	Okamoto-Mizuno & Mizuno (2012)
Menopausal women with night sweats	Phase-change material pillow/mattress	Sleep disturbance index, night sweats frequency	Reduced awakenings, fewer hot-flash-related arousals	Potter et al. (2025)
Healthy adults (field study)	Portable wrist cooling device	HRV, sleep diaries, cortisol	Improved relaxation, higher HRV, decreased cortisol	Montaruli et al. (2021)
Elderly patients with poor sleep	Mattress topper with airflow system	Sleep continuity, total sleep time (actigraphy)	Better sleep continuity, longer total sleep time	Hu & Liang (2023)
PTSD patients with insomnia	Scalp/forehead cooling device	Subjective sleep quality, nighttime cortisol	Improved perceived rest, lowered nighttime cortisol	Harvey et al. (2018)

4.3 Forehead Cooling

Forehead-targeted devices represent one of the most clinically promising cooling methods which can directly influence the thermoregulation and central nervous system reactions. This sub-section is chosen especially due to the duality in the relevance of sleep improvement and migraine management, which are highlighted in the project brief.

Mechanisms of forehead cooling: The forehead and the scalp are highly innervated areas and cooling of the forehead can affect both superficial and deeper parasympathetic cooling through trigeminal and vagal pathways. Okamoto-Mizuno and Mizuno (2012) point out that the application of mild cooling of head depresses CBT better as compared to the use of peripheral interventions alone, which facilitates the initiation and maintenance of sleep.

Supporting sleep results: There is clinical evidence that forehead cooling devices decrease sleep onset latency, night awakening and subjective sleep quality more than sham controls (Castelli et al., 2022). These devices in insomnia populations treat the hyperarousal of these populations by providing thermal comfort but with vagal activation, which results in increased parasympathetic dominance.

Forehead cooling and migraine: Forehead cooling has also been demonstrated to reduce the effect and frequency of migraine. In a global cross-sectional study, Stanyer et al. (2023)

describe that the sleep disruption and migraine were strongly connected, and the intervention that enhanced one aspect of the domain tended to enhance the other. Cooling the forehead with devices such as gel cooling systems or electronic cooling systems which use thermoelectric cooling have shown decreased sleep complaints and reduced severity of migraines (Buguet et al., 2023).

Special populations: These devices are particularly applicable to the patients, who cannot use pharmacological methods of insomnia or migraine treatment, or those who want non-invasive add-ons (Castelli et al., 2022). They are also portable and have a good safety profile that facilitates their clinical adoption.

Integration into treatment: According to Potter et al. (2025), forehead cooling (when used with behavioral sleep interventions e.g., CBT-I) improves the effectiveness of the therapy. Forehead cooling devices applied together with adequate sleep hygiene and circadian regulation can potentially treat physiological and psychological aspects of sleep disturbance.

5. Therapeutic Relevance and Future Directions

5.1 Integration of Cooling as Adjunct Therapy with CBT-I

Cognitive Behavioral Therapy of Insomnia (CBT-I) is generally considered the most effective type of non-pharmacological treatment of chronic insomnia. Nevertheless, certain remnant symptoms remain, especially those associated with hyperarousal and thermal pain even following CBT-I (Ngarambe et al., 2019). Cooling therapies are a promising adjunct with direct effect on physiological barriers of high core body temperature and ineffective thermoregulation. CBT-I protocols should include the use of cooling devices (i.e., forehead coolers, cooling mattresses) to make sleep onset less often and nocturnal awakenings fewer, as well as to reinforce behavioral advice such as regular sleep-wake schedules (Altena et al., 2022). Besides, CBT-I and cooling combination is consistent with stimulus control and relaxation training. Cooling interventions could promote patient adherence and decrease the dropout rates by lowering hyperarousal and supporting parasympathetic dominance, which prove to be ongoing problems in the CBT-I practice (Baranwal et al., 2023).

5.2 Applications for Stress-Related Insomnia, Anxiety, and Migraines

Insomnia caused by stress is among the most prevalent sleeping disorders in the world, and it is usually not responsive to any conventional means. It is demonstrated that cooling strategies dull HPA axis activity and reduce cortisol, which is why they are the only strategies to combat physiological reactions to stress (Buguet et al., 2023). Patients who suffer anxiety disorders can also have the advantage, since cooling improves vagal activation, which promotes a relaxing physiological state, enhancing psychotherapeutic strategies. Cooling machines on the forehead are particularly applicable where the patient has comorbid migraine. These devices, which decrease cortical hyperexcitability and are used to control blood flow, are used not only to achieve a better quality of sleep but also to decrease the severity and frequency of migraine episodes (Hong et al., 2022). Stanyer et al. (2023) also clarified that the reduction of sleep disruption in migraineurs can help to reduce migraine burden itself, which forms a synergistic treatment loop.

5.3 Research Gaps: Long-Term Effectiveness, Cost, Accessibility, and Adoption Barriers

Although there are promising results of short-term trials, there are still large gaps in research. Ecological validity has been limited by most studies being performed in a controlled laboratory environment. Longitudinal studies are also badly required to determine the effectiveness of cooling interventions in the long run (months or years) (Habibi et al., 2024). Barriers are also in the form of cost and accessibility. The use of sophisticated cooling mattresses and wearable gadgets is frequently costly to an extent that constrains their usage. Moreover, one should remember the cultural and regional variability of housing infrastructure and climate: in the case of tropical settings, people will have more difficulties with the optimal thermal conditions despite the interventions (Hu and Liang, 2023). The barriers to adoption spread to the clinical practice as well. The sleep specialists and therapists might not be keen on using cooling because they do not have standardized procedures, they are not properly trained, or they are doubtful of the technological adjuncts (Altena et al., 2022). This highlights the need to have high-quality randomized controlled trials and meta-analyses to strengthen the evidence base and drive guidelines.

5.4 Recommendations for Future Studies and Clinical Integration

Future research should prioritize:

- **Large-scale, multi-center trials** assessing the long-term benefits of cooling devices across diverse populations, including elderly, menopausal women, and individuals with comorbid psychiatric or neurological conditions (Habibi et al., 2024).
- **Integration into CBT-I protocols**, with studies measuring not only sleep outcomes but also adherence and patient satisfaction (Hu & Liang, 2023).

- **Cost-effectiveness analyses** to evaluate affordability and guide insurance coverage decisions.
- **Personalized cooling strategies**, leveraging biomarkers such as circadian chronotype, distal–proximal skin temperature gradient, and HRV to tailor interventions (Montaruli et al., 2021).
- **Climate change considerations**, as global warming and heatwaves increase the urgency of resilient sleep environments (Bach & Libert, 2022).

By addressing these areas, cooling can evolve from a promising adjunct into a mainstream therapeutic modality within behavioral sleep medicine.

6. Conclusion

Cooling interventions are a concept with strong potential in sleep medicine that is not used to its full potential. In keeping with basic physiological processes core body temperature drop, vasodilation of peripheral blood vessels, and parasympathetic activation, direct cooling targets the barriers most frequently linked to insomnia, stress-related sleeping disorders and migraines. Flexible encompassment into behavioral practice is not only possible, but complementary. These can be combined with CBT-I and sleep hygiene suggestions and layered over whether it is optimized bedroom conditions, cooling mattresses, or forehead devices to achieve synergistic changes. Notably, cooling can also help in the growing problem of sleep disturbance, which is climate-related, and provide a non-pharmacological and environmentally responsive remedy.

The applicability of cooling is long lasting due to its bilateral effects on sleep and stress. Cooling also helps to reduce hyper-arousal, cortisol, and autonomic imbalance, enhancing restful sleep and resilience to stress-related disorders. Moreover, its role in migraine treatment is proven to demonstrate its neuroprotective and therapeutic possibilities in general. In the future, the adoption of cooling measures in clinical practice, education of patients, and the international health policy will be crucial. As further studies and practical inventions are made, cooling can move to an experimental supplement, but to become a key part of a holistic sleep and stress management system.

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