Proceedings of ICBioMed 2025 Symposium: AI for Healthcare: Advanced Medical Data Analytics and Smart Rehabilitation
DOI: 10.54254/2753-8818/2025.AU25267

Exploring the Role of the Central Nervous System in Cardiovascular Health and Function

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Abstract. The National Institutes of Health has reported that cardiovascular disease remains one of the leading causes of death across the United States. In recent years, more and more studies emphasize the central nervous system (CNS) as a critical regulator of cardiovascular function, hence serving as an active participant rather than just a passive responder. This paper aims to investigate the critical role of the CNS in regulating cardiovascular function, with particular attention to its involvement in stress regulation, heart rate modulation, and neural plasticity. Emotional stress can significantly impact specific brain regions such as the amygdala and insular cortex, which in turn alters heart rate variability (HRV) and elevates the long-term risk of cardiovascular disease. To assess progress in the field, it integrates significant findings from contemporary research addressing both the physiological basis and treatment possibilities of CNS-cardiovascular interactions. Special attention is given to the role of neural plasticity in clinical regulation. By analyzing existing literature, this paper seeks to establish a theoretical basis for understanding brain-heart coupling and to facilitate the development of CNS-targeted intervention strategies. The results reveal that prolonged chronic stress may cause measurable changes in brain structure, disrupting cardiovascular regulatory balance. However, the plasticity of the CNS provides the body with the potential for recovery and adaptation. This mechanism lays a theoretical foundation for various CNS-targeted interventions, including yoga, vagus nerve stimulation, and leptin administration, all of which have shown promising effects in improving cardiovascular function.

Keywords: Central nervous system (CNS), Cardiovascular regulation, Heart rate variability (HRV), Emotional stress, Neuroplasticity

1. Introduction

The central nervous system (CNS) plays a key role in cardiovascular regulation by controlling heart rate, blood pressure, and other vascular responses through a complex network of brain regions and neural pathways. Emotional and physiological stimuli are processed by CNS structures such as the hypothalamus, amygdala, insular cortex, and brainstem, which affect the autonomic nervous system, enabling dynamic responses to the biological demands of both internal and external environments. The regulation of the stress response by the CNS stands out as a particularly important mechanism among many. When stress activates neural pathways in the hypothalamus, amygdala, and brainstem, it triggers immediate autonomic responses as well as prolonged neuroendocrine changes [1]. These

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effects of emotional stress can cause short-term fluctuations in heart rate and blood pressure and contribute to an increased long-term risk of cardiovascular disease. Moreover, the CNS regulates heart rate via neural mechanisms that allow the cardiovascular system to adapt flexibly to changing physiological and emotional stimuli. Heart rate variability (HRV), a critical measure of autonomic function and cardiovascular health, is strongly associated with CNS regulation and prefrontal cortex activity [2]. Dysregulation in these processes is often associated with heightened disease risk and decreased adaptability. Increasing evidence shows that CNS neuroplasticity drives adaptive changes that boost cardiovascular function and reduce disease risk. This plasticity is evident in brain regions like the insular and prefrontal cortices and can be enhanced via behavioral interventions including exercise, meditation, and biofeedback [3,4]. These neuroplastic changes restore autonomic balance and resilience, forming the basis for cardiovascular therapies. This review integrates recent research on the relationship between the CNS and cardiovascular health, with a focus on three interrelated areas, namely the regulation of cardiovascular function by the CNS, its influence on heart rate and autonomic nervous system activity, and the potential of neuroplasticity to enhance cardiovascular outcomes. In particular, it examines how CNS regions regulate emotional stress responses, adapt to behavioral influences, and support therapeutic interventions. Deeper insight into these processes can inform the development of innovative CNS-based treatments for cardiovascular health.

2. Regulation of cardiovascular function by the central nervous system

The CNS regulates cardiovascular function through the autonomic nervous system, sympathetic and parasympathetic branches, and key control centers like the hypothalamus, brainstem, and higher cortical regions. These networks adjust heart rate, vascular resistance, and baroreceptor reflexes in response to physical and emotional stimuli. Research shows that CNS signals from areas such as the insular and anterior cingulate cortices play a key role during exercise and stress [4].

2.1. Emotional stress and cardiovascular interventions

Emotional stress have profound effects on CNS function, activating regions involved in emotional processing, autonomic regulation, and cardiovascular control. As a key indicator of parasympathetic (vagal) regulation of cardiac function, HRV, particularly high-frequency HRV (HF-HRV), is widely used to measure autonomic flexibility and CNS responses to stress and emotional stimuli. During emotional stress, studies consistently report a decrease in HF-HRV, signaling reduced vagal tone. For example, Lane et al. observed that HF-HRV significantly decreased during negative emotions like disgust and sadness compared to neutral states, indicating that emotional arousal can suppress parasympathetic activity [5]. This physiological reduction in HRV serves as an early indicator of emotional stress processing within the CNS. More importantly, prolonged reductions in HRV have been robustly associated with adverse cardiovascular outcomes. Persistent low HRV correlates with heightened risks of hypertension, cardiovascular disease, metabolic syndrome, as well as increased mortality [6]. These observations imply that impaired CNS capacity to modulate autonomic output flexibly in response to emotional stress may drive worsening cardiovascular dysfunction over time. Further supporting the CNS's mediating role, neuroimaging studies by Gianaros and Wager showed that emotional stress triggers activation in key brain regions like the amygdala and periaqueductal gray (PAG), which play key roles in affective and autonomic regulation [7]. Notably, they observed that activation volume in these regions doubled alongside increases in HF-HRV during stress, thus indicating a direct link between HRV and CNS activity in emotional regulation. Similarly, Lane et al. found strong HRV correlations with blood flow in key emotion and autonomic areas [5]. This

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connects emotional stress to impaired CNS regulation of HRV, where low HRV signals emotional imbalance and higher cardiovascular risk.

2.2. Chronic stress and structural brain changes

Prolonged exposure to chronic stress induces major and lasting alterations in brain regions involved in emotional regulation and autonomic control. In rodent models, McEwen showed that prolonged stress exposure causes notable dendritic remodeling in essential brain regions like the hippocampus, prefrontal cortex, and amygdala [1]. These structural modifications are region-specific and exhibit distinct directional patterns: chronic stress results in reduced dendritic length and branching in the hippocampus and medial prefrontal cortex, indicative of neuronal atrophy and impaired top-down regulatory function, whereas the amygdala exhibits increased dendritic arborization, thus reflecting enhanced emotional reactivity and fear processing.

Importantly, these neural alterations extend beyond cognitive and affective domains to directly influence cardiovascular regulation. The prefrontal cortex and hippocampus are key components of the central autonomic network (CAN), regulating heart rate, blood pressure, and vagal tone. When these regions are damaged, their ability to inhibit the hypothalamic-pituitary-adrenal (HPA) axis and sympathetic nervous system is reduced, causing prolonged autonomic imbalance. Specifically, diminished prefrontal inhibition facilitates increased sympathetic output, contributing to elevated resting heart rate and blood pressure,recognized risk factors for cardiovascular disease [8]. Thus, these findings from animal research underscore the mechanistic link between chronic stress-induced brain remodeling and subsequent cardiovascular dysfunction.

3. Modulation of heart rate and cardiovascular health by the central nervous system

3.1. The CNS modulation of heart rate and and cardiovascular function

The CNS plays a pivotal role in regulating heart rate through key brain regions such as the insular cortex, which is activated during exercise independently of muscle contractions or blood pressure changes. For example, during static handgrip (SHG) exercise, heart rate increased by 7 ± 3.3 bpm, while mean blood pressure rose from 94 ± 7 mmHg to 108 ± 5 mmHg. SPECT imaging revealed increased cerebral blood flow in the anterior cingulate cortex (6 ± 2%) and right inferior thalamus (15 ± 3%), reflecting activation of central command mechanisms [14]. HRV and heart rate are also significantly influenced by emotional stress. In individuals with PTSD, elevated resting heart rate and blood pressure are linked to HPA axis dysregulation, characterized by reduced ventromedial prefrontal cortex (vmPFC) activity and heightened amygdala activation [9]. These changes impair autonomic balance by reducing vagal tone and increasing sympathetic drive. Furthermore, CNS dysfunction can precipitate severe cardiac events. In animal models, stimulating the insular cortex in rats led to heart rate shifts of around 18 bpm and triggered severe arrhythmias and sudden death, highlighting the cortex's direct role in cardiac control [10].

3.2. The CNS plasticity and its impact on enhancing cardiovascular health

Neuroplasticity, defined as the brain's capacity to undergo structural and functional modifications in response to environmental stimuli, has emerged as a fundamental mechanism underlying central regulation of cardiovascular function. Factors such as stress and physical activity can modulate autonomic balance and neurotransmission within central circuits. Beauchaine and Thayer reported that neuroplastic changes in the prefrontal and insular cortices enhance HRV, a robust indicator of

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cardiovascular health [11]. Further supporting this link, Omoto et al. demonstrated that continuous leptin administration (0.62 μg/h for 28 days) improved post-infarction cardiac outcomes in rats. Leptin-treated male rats exhibited a 35% improvement in left ventricular ejection fraction (LVEF), while females showed a 25% increase; infarct size was reduced by approximately 5% in males and 20% in females. More importantly, leptin administration preserved post-myocardial infarction (MI) exercise capacity, in contrast to control animals, which experienced an approximate 50% decline [12]. Moreover, stimulation or lesioning of the hypothalamic paraventricular nucleus (PVN) and nucleus tractus solitarius (NTS) disrupted cardiovascular regulation in rats, underscoring these regions' involvement in autonomic control [13]. Behavioral interventions like yoga may also exert cardioprotective effects through CNS plasticity. In individuals with major depressive disorder, a 12-week yoga program resulted in a 25% increase in thalamic GABA levels, along with improved heart rate variability and decreased perceived stress [14]. These findings indicate that both behavioral and pharmacological interventions can enhance CNS plasticity, hence presenting promising avenues for the treatment of stress-related and chronic cardiovascular conditions.

4. Potential of cns-based interventions in cardiovascular therapy

Emerging evidence emphasizes the therapeutic potential of interventions targeting the CNS to boost cardiovascular function [12-14]. These strategies like pharmacological treatments, neurostimulation, and behavioral therapies, act on key brain regions such as the hypothalamus, amygdala, insular cortex, and brainstem to modulate cardiovascular regulation and support sustained cardiovascular health. The following sections provide a systematic overview of these intervention strategies.

4.1. Mind-body interventions: yoga and neurotransmitter modulation

Yoga, which combines physical postures with mindfulness practices, has been shown to positively influence emotional regulation and cardiovascular health through CNS mechanisms. Streeter et al. demonstrated that a 12-week yoga intervention resulted in a 25% increase in thalamic gamma-aminobutyric acid (GABA) levels in patients diagnosed with major depressive disorder [14]. This neurochemical change was accompanied by improvements in HRV and reductions in perceived stress, suggesting enhanced autonomic function. The elevation of inhibitory neurotransmitters such as GABA is indicative of increased parasympathetic tone, which supports better autonomic balance and cardiovascular resilience. These findings highlight yoga as a promising, non-invasive approach for reducing stress-related cardiovascular risk by facilitating CNS neuroplasticity.

4.2. Pharmacological intervention: leptin and hypothalamic circuitry

Leptin, a hormone known for its CNS effects, has demonstrated cardioprotective properties when administered directly to the CNS. In a study by Omoto et al., leptin was delivered at a rate of 0.62 μg/h for 28 days to 180 rats following MI [12]. The treatment resulted in a notable improvement in left ventricular ejection fraction (LVEF), increasing by 35% in males and 25% in females. Besides, infarct size was reduced by approximately 5% in males and 20% in females, while exercise capacity post-MI was preserved. These beneficial effects were linked to leptin's regulation of hypothalamic neurocircuits that maintain cardiovascular homeostasis. Moreover, leptin-treated animals exhibited decreased food intake and body weight, thus indicating potential therapeutic benefits in managing obesity and metabolic disorders frequently comorbid with cardiovascular disease.

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4.3. Neuromodulation: vagal nerve stimulation and brainstem circuits

Vagal nerve stimulation (VNS) provides a neuromodulatory method that directly targets brainstem centers governing cardiovascular function. Kannan and Yamashita demonstrated in rats that both stimulation and lesioning of the paraventricular nucleus (PVN) and nucleus tractus solitarius (NTS) markedly disrupted cardiovascular regulation [13]. These brainstem nuclei are key components of the baroreflex and autonomic control systems. VNS may promote stabilization of blood pressure, HRV, and heart rate by enhancing parasympathetic activity and suppressing sympathetic overdrive via direct CNS-cardiovascular feedback mechanisms.

5. Future directions and clinical considerations

Despite the promising evidence, the implementation of CNS-based interventions in routine clinical cardiovascular care remains challenging. Individual variability in neuroanatomy and physiological responses, the intricate nature of central neural circuits, and potential side effects of brain-targeted therapies like leptin all require careful consideration to ensure safe and prudent clinical application. Future research should focus on identifying reliable biomarkers that reflect CNS-cardiovascular connectivity, which could allow clinicians to objectively monitor the impact of interventions. In addition, investigating specific neurotransmitters and pathways, particularly within the PVN-NTS axis, may facilitate the development of precision-targeted therapies addressing the neural basis of cardiovascular dysfunction. Moreover, optimizing treatment strategies by integrating non-invasive methods like yoga with pharmacological interventions will be crucial for enhancing clinical efficacy and increasing the reach of CNS-targeted cardiovascular therapies.

6. Conclusion

This paper has demonstrated the effect of the CNS on cardiovascular function through its regulation in stress response, heart rate modulation, and neural plasticity, while evaluating various potential therapeutic interventions. The results show that the CNS impacts heart rate variability and cardiac output through brain regions like the amygdala and insular cortex, which are involved in emotional and autonomic regulation. Dysfunction in these CNS areas is significantly associated with increased cardiovascular risk in conditions like PTSD and other stress-related disorders. Also, interventions like leptin administration and behavioral therapies like yoga enhance neuroplasticity, contributing to the restoration of autonomic regulation and the improvement of cardiac function. In short, CNS-targeted therapies advance the understanding of cardiovascular disease pathophysiology and open promising new avenues for clinical treatment. Future studies should prioritize developing precise interventions aimed at specific CNS neural circuits to optimize cardiovascular outcomes.

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