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Research Progress on the Mechanisms of Acupuncture in the Treatment of Spinal Cord Injury

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Abstract: Spinal cord injury (SCI) is a highly disabling neurological condition, for which effective treatment options remain scarce. Acupuncture, as a traditional Chinese medical therapy, has demonstrated significant clinical value in promoting functional recovery following SCI. This paper systematically reviews the research progress on the mechanisms of acupuncture in SCI treatment, focusing on its effects in neural repair, inflammation regulation, oxidative stress alleviation, and neural network reconstruction. Furthermore, it summarizes experimental and clinical research findings while highlighting their limitations. The paper also discusses technical challenges in acupuncture mechanism studies and explores future research directions, emphasizing the importance of multidisciplinary approaches in understanding acupuncture's mechanisms. This study aims to provide theoretical support and practical guidance for both basic research and clinical applications of acupuncture in SCI treatment.

1. Introduction

Spinal cord injury (SCI) is a severe central nervous system condition caused by trauma, disease, or degenerative changes. Its primary characteristic is the partial or complete disruption of neural conduction pathways, leading to impairments in motor, sensory, and autonomic functions, with profound impacts on patients' quality of life and socioeconomic conditions. Despite progress in modern medicine, effective therapeutic methods targeting neural function recovery are still lacking. Therefore, exploring comprehensive treatments, particularly those that promote neural repair and functional restoration, has become a central focus in this field. Acupuncture, a core therapy in traditional Chinese medicine (TCM), has long been widely applied to treat various neurological disorders due to its simplicity, cost-effectiveness, and efficiency[1]. In recent years, the potential of acupuncture in SCI treatment has garnered increasing attention. Modern studies have shown that acupuncture not only modulates central nervous system functions but also promotes recovery through mechanisms such as neural repair, inflammation suppression, oxidative stress alleviation, and neural network reconstruction. The exploration of these mechanisms provides scientific support for acupuncture in SCI treatment and opens new avenues for the modernization and internationalization of TCM. Although experimental and clinical studies have provided preliminary evidence for the efficacy of acupuncture in SCI treatment, challenges remain, such as insufficient

depth in mechanism studies and the lack of standardization in experimental designs and clinical trials. Moreover, acupuncture mechanism studies involve multiple disciplines, including neuroscience, immunology, and biochemistry, which face technical and theoretical bottlenecks that limit further progress. Systematically summarizing the research progress on the mechanisms of acupuncture in SCI treatment, reviewing current findings and limitations, is crucial for advancing basic research and clinical applications in this field. This paper reviews the theoretical foundations, mechanisms, and current experimental and clinical research on acupuncture in SCI treatment. It further analyzes key challenges in current studies and explores future research directions, aiming to provide theoretical support and practical references for scientific research and clinical practice in acupuncture for SCI treatment[2].

2. Theoretical Foundations of Acupuncture in the Treatment of SCI

In TCM, SCI is often understood as a pathological condition caused by “blocked meridians” and “disrupted qi and blood flow.” The meridian theory posits that meridians are pathways for qi and blood circulation, linking internal organs with extremities. Their unobstructed flow directly impacts overall health. SCI disrupts qi and blood circulation and impairs meridian conduction, leading to insufficient nutritional supply to local tissues and functional impairments. Additionally, TCM classifies SCI under the category of “wei syndrome,” which is closely related to deficiencies in the liver, kidney, spleen, and stomach. Acupuncture treatment stimulates specific acupoints along the meridians, facilitating meridian clearance, regulating qi and blood flow, and improving local microcirculation. According to TCM classics, acupuncture operates on the principle of “unblocking to alleviate pain,” achieving balance between yin and yang and promoting blood flow to relieve pain and restore function in SCI patients[3]. By targeting relevant acupoints near the injury site (e.g., along the Governor Vessel and Bladder Meridian), acupuncture can regulate organ functions and improve physiological conditions in the affected area, promoting overall recovery. From a modern medical standpoint, the mechanisms of acupuncture are increasingly elucidated through neuroscientific research. Acupuncture mechanically stimulates receptors in the skin or muscles, activating afferent nerve fibers and triggering a cascade of neural responses. These responses are transmitted via neural networks to the central nervous system, inducing neuroendocrine modulation and neurotransmitter release, which contribute to biological effects. In SCI treatment, acupuncture likely exerts positive effects on injured neural tissue by modulating neural conduction and plasticity. Studies have demonstrated that acupuncture promotes neural regeneration and axonal growth, enhancing functional connectivity within neural networks near the injury site. Furthermore, acupuncture has been shown to regulate synaptic plasticity in the brain and spinal cord, improving communication efficiency between neurons. This regulation is mediated by neurotransmitter balance (e.g., dopamine, acetylcholine, and glutamate), reducing functional impairments caused by SCI. Additionally, acupuncture promotes the expression of neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), aiding tissue repair and functional reconstruction. These findings provide reliable evidence for the scientific application of acupuncture in SCI treatment. In summary, acupuncture mechanisms in SCI treatment have a robust theoretical foundation and practical support from both TCM and modern medical perspectives. Integrating these perspectives offers new possibilities for further exploring acupuncture mechanisms and expanding its clinical applications[4].

3. Mechanisms of Acupuncture in the Treatment of Spinal Cord Injury

3.1. Neural Repair

Acupuncture demonstrates significant therapeutic potential in neural repair following spinal cord injury (SCI), with mechanisms primarily involving the promotion of neural regeneration, enhancement of axonal growth, and improvement in myelin remodeling. Neural damage from SCI is often accompanied by axonal severance, neuronal death, and myelin loss—key pathological changes that lead to functional impairments. Recent studies, both experimental and clinical, have made breakthroughs in understanding how acupuncture facilitates neural repair. Research shows that acupuncture can stimulate specific meridian points near the injury site, activating signaling pathways associated with neural regeneration to promote the survival and regeneration of damaged neurons. For instance, experimental data indicate that acupuncture significantly increases the expression of brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF)[5]. These factors promote the proliferation and differentiation of neural cells while enhancing axonal regeneration, laying a structural foundation for the restoration of functional connections between neurons. Furthermore, acupuncture modulates vascular endothelial growth factor (VEGF) release, improving local tissue blood supply, thus creating a favorable microenvironment for tissue repair. Acupuncture's role in regulating myelin remodeling has also garnered attention. Myelin loss in SCI impairs neural signal transmission efficiency, but acupuncture promotes the activation and differentiation of oligodendrocytes, accelerating myelin regeneration. Some studies have also found that acupuncture inhibits the expression of myelin inhibitory factors, such as Nogo proteins, further enhancing myelin remodeling efficiency. Additionally, acupuncture's role in neural repair may be linked to its ability to regulate the neural microenvironment[6]. By modulating the expression of inflammatory factors, acupuncture alleviates inflammation at the injury site, reducing secondary neuronal damage. It also adjusts oxidative stress levels, minimizing free radical-induced neural tissue damage, and providing optimal conditions for neural repair. In summary, acupuncture facilitates neural repair in SCI through multi-level and multi-target mechanisms, including neural regeneration, axonal growth, myelin remodeling, and microenvironment regulation. These integrated effects provide a solid scientific foundation for acupuncture’s application in SCI treatment and highlight promising directions for further research on its neural repair mechanisms[7].

3.2. Inflammation Regulation

Inflammatory responses following SCI are a critical pathological process leading to secondary damage and functional impairments. Immune cell hyperactivation and excessive release of pro-inflammatory cytokines exacerbate neural tissue destruction, hindering neural repair. Effectively modulating the inflammatory response has thus become a crucial focus in SCI treatment. Recent studies indicate that acupuncture can regulate inflammation through multiple pathways, reducing secondary damage and promoting functional recovery. Firstly, acupuncture significantly reduces pro-inflammatory cytokine levels after SCI. Experimental research shows that acupuncture inhibits the overexpression of key pro-inflammatory cytokines, such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β). Reducing these cytokines alleviates inflammation at the injury site, decreasing inflammation-induced neural apoptosis and tissue damage. Simultaneously, acupuncture increases anti-inflammatory cytokines, such as interleukin-10 (IL-10), establishing a balance between pro- and anti-inflammatory factors to improve the injury site’s microenvironment. Secondly, acupuncture’s regulation of immune cell activity is a critical component of its inflammation-regulating mechanism[8]. After SCI, activated microglia and

macrophages release large amounts of inflammatory mediators, causing further tissue damage. Studies suggest that acupuncture downregulates the activation levels of microglia and macrophages, reducing their invasive responses at the injury site. Additionally, acupuncture promotes the proliferation and function of regulatory T cells (Tregs), suppressing excessive immune reactions and aiding tissue repair. Moreover, acupuncture modulates inflammation-related signaling pathways to achieve its anti-inflammatory effects. For example, research indicates that acupuncture inhibits the activation of the nuclear factor kappa B (NF-κB) signaling pathway, blocking the expression of pro-inflammatory genes and reducing the release of inflammatory cytokines. This mechanism is crucial for controlling post-injury inflammatory cascades and provides a scientific basis for studying the molecular mechanisms of acupuncture. In conclusion, acupuncture exerts critical anti-inflammatory effects by reducing pro-inflammatory cytokines, enhancing anti-inflammatory cytokines, modulating immune cell activity, and intervening in inflammation-related signaling pathways. These multi-target inflammation-regulating effects help mitigate secondary damage and create favorable conditions for neural repair and functional recovery. Future research on acupuncture's molecular mechanisms in inflammation regulation will provide more theoretical and practical support for precision SCI treatments[9].

3.3. Oxidative Stress and Metabolic Regulation

Oxidative stress is a key driver of secondary damage following SCI. Excessive production of free radicals and an imbalance in the antioxidant system cause further damage to neural cells, including lipid peroxidation, protein degradation, and DNA breakage, exacerbating neuronal death and functional loss. Acupuncture has been shown to play a critical role in reducing oxidative stress and correcting metabolic imbalances, contributing to SCI treatment. Research demonstrates that acupuncture effectively mitigates oxidative stress by regulating the production and clearance of free radicals. On the one hand, acupuncture significantly reduces the levels of reactive oxygen species (ROS) and reactive nitrogen species (RNS), the primary molecules responsible for oxidative damage. On the other hand, acupuncture enhances the activity of antioxidant enzymes such as superoxide dismutase (SOD), glutathione peroxidase (GSH-Px), and catalase (CAT). These enzymes play vital roles in scavenging free radicals and protecting neural cells from oxidative stress. Acupuncture also modulates redox signaling pathways, such as the Nrf2-ARE pathway, promoting the expression of antioxidant genes and enhancing cellular resilience to oxidative stress.In terms of metabolic regulation, acupuncture improves energy metabolism and the microenvironment of local tissues, facilitating SCI repair. Acupuncture regulates glucose metabolism, promotes tricarboxylic acid cycle (TCA) activity, and increases cellular energy supply[10]. Additionally, acupuncture modulates lactate production and clearance, reducing acidotic microenvironments caused by lactate accumulation and improving metabolic conditions at the injury site. Studies also reveal that acupuncture regulates mitochondrial function, enhancing ATP production and reducing mitochondria-mediated apoptosis, which is crucial for maintaining neural cell energy balance.It is noteworthy that acupuncture's role in metabolic regulation also involves cytokine modulation. Acupuncture increases levels of neurotrophic factors such as BDNF and NGF, which are essential for neural cell survival and regeneration and support metabolic improvements in the injured area. Furthermore, acupuncture regulates nitric oxide (NO) production and metabolism, promoting vasodilation and blood flow to alleviate tissue hypoxia and create a conducive metabolic environment for neural repair.In summary, acupuncture alleviates oxidative stress, enhances antioxidant capacity, and optimizes metabolic balance to support functional recovery from SCI. This dual regulatory effect reduces secondary damage and fosters neural repair and tissue regeneration. Future studies can further investigate the specific molecular mechanisms of

acupuncture in oxidative stress and metabolic regulation, providing deeper theoretical and technical support for its application in SCI treatment.

3.4. Neural Network Reconstruction

Reconstructing neural networks is a critical step in functional recovery following SCI. SCI typically results in axonal disruption and network interruption, impairing the transmission of functional signals and causing disconnection between the injury site and upstream and downstream neural regions. Acupuncture facilitates neural network reconstruction through multiple mechanisms, improving neural pathway integrity and providing promising possibilities for long-term SCI recovery. Research indicates that acupuncture promotes axonal regeneration and synaptic plasticity, providing the structural foundation for neural network reconstruction. Animal studies have shown that acupuncture significantly increases the density of newly formed axons near the injury site and enhances axonal growth. This regenerative effect is closely linked to acupuncture's upregulation of neurotrophic factors such as BDNF and NT-3, which play critical roles in axonal growth, synaptic formation, and network stabilization. Furthermore, acupuncture activates both local and systemic neural circuits by stimulating specific meridian points, fostering functional connections between neurons and accelerating neural network reorganization. Acupuncture also regulates synaptic plasticity, enhancing the functional recovery of neural networks. Synaptic plasticity, the core of neural network reconstruction, involves dynamic adjustments in synaptic strength and quantity. Studies show that acupuncture modulates neurotransmitter release, such as glutamate, dopamine, and acetylcholine, promoting long-term potentiation (LTP) at synapses. This enhancement of synaptic strength not only improves information transmission efficiency at the injury site but also facilitates neuroadaptive changes in upstream and downstream regions. Additionally, acupuncture modulates synaptic structural proteins, such as PSD-95, to stabilize synaptic structures, laying the foundation for long-term functional recovery. Acupuncture's effects on neural network reconstruction extend to the redistribution of neural signals across regions. Functional magnetic resonance imaging (fMRI) studies reveal that acupuncture activates multiple brain and spinal regions, promoting information transmission across neural circuits. This helps overcome the isolated state caused by SCI, restoring coordination between different neural regions and enhancing overall neural network function.Moreover, acupuncture improves the neural microenvironment, supporting neural network reconstruction. Acupuncture increases local blood flow, improves oxygen delivery, and facilitates the removal of metabolic waste, creating favorable conditions for the survival of damaged neurons and newly formed synapses, thereby accelerating neural network recovery.In conclusion, acupuncture promotes neural network reconstruction through mechanisms such as axonal regeneration, enhanced synaptic plasticity, and improved neural microenvironment. These effects provide critical support for functional recovery following SCI and highlight acupuncture's vast potential in neural repair. Future studies should involve larger-scale experiments and clinical trials to validate the specific effects and mechanisms of acupuncture in neural network reconstruction, laying a solid foundation for its clinical application.

4. Experimental and Clinical Research Status of Acupuncture in Spinal Cord Injury Treatment

In recent years, the mechanisms of acupuncture in treating spinal cord injury (SCI) have become a focus of experimental research. Studies using animal models have provided crucial insights into the biological effects of acupuncture. In rat models of SCI, acupuncture significantly improves motor function recovery, primarily through mechanisms related to neural repair, inflammation suppression, and oxidative stress regulation. For example, research on a transected spinal cord rat

model shows that acupuncture at points such as “Zusanli” (ST36) and “Baihui” (GV20) significantly increases the expression levels of brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF) in spinal tissue, promoting neural regeneration. Additionally, acupuncture has been shown to reduce inflammatory cell infiltration in the injured area by lowering pro-inflammatory factors such as TNF-α and IL-6, thereby improving the post-injury microenvironment. On a molecular level, experimental studies have found that acupuncture enhances neuron survival and promotes axonal growth by regulating key signaling pathways such as PI3K/Akt, MAPK, and NF-κB. Moreover, acupuncture has demonstrated a protective effect on mitochondrial function by reducing activity in apoptosis-related pathways, such as those involving caspase-3, thereby protecting neural cells from further damage. These findings reveal the potential mechanisms of acupuncture in SCI treatment across molecular, cellular, and systemic levels, providing a solid scientific basis for further research. Acupuncture has a long history of clinical application in SCI treatment, and recent studies have further validated its efficacy while broadening its applications. Multiple clinical trials have demonstrated that acupuncture significantly improves motor and sensory functions and enhances the quality of life for SCI patients. In randomized controlled trials, patients receiving acupuncture combined with rehabilitation training showed marked improvements in American Spinal Injury Association (ASIA) scores, particularly in motor function recovery. Furthermore, acupuncture has shown efficacy in alleviating SCI-related complications. For instance, acupuncture effectively reduces neuropathic pain and muscle spasms in SCI patients, likely due to its regulation of neurotransmitters such as endogenous opioids and norepinephrine. Other studies have explored its effects on bladder dysfunction following SCI, showing that acupuncture improves bladder contraction and urinary control, leading to a better quality of life for patients. Despite the promising outcomes in efficacy evaluations, clinical studies face several limitations. Many studies are constrained by small sample sizes and lack multicenter, large-scale randomized controlled trials. Additionally, standardization issues remain a significant challenge, including variability in acupoint selection, manipulation techniques, and treatment duration, which affect the comparability and generalizability of research findings. Experimental research has provided initial evidence for the biological mechanisms of acupuncture in SCI treatment, while clinical studies have confirmed its practical effects on functional recovery. However, further efforts are needed to expand its application: increasing the scale of multicenter clinical trials to validate the generalizability of acupuncture’s effects, using modern technologies such as functional magnetic resonance imaging (fMRI) and molecular biology techniques to deeply analyze its mechanisms, and establishing international standards for acupuncture in SCI treatment to facilitate global promotion and application. These efforts will help transition acupuncture from a traditional therapy to a scientifically validated modern medical intervention, offering new hope for SCI patients.

5. Challenges in Current Research and Future Prospects

Despite progress in research on acupuncture for SCI treatment, several challenges remain. Firstly, in terms of mechanism studies, the molecular and cellular mechanisms of acupuncture are not fully elucidated. Existing research primarily focuses on single pathways or specific factors, such as changes in BDNF or NGF, while acupuncture likely involves multi-pathway and multi-level synergistic effects. Systematically uncovering the comprehensive mechanisms of acupuncture in neural repair, inflammation regulation, oxidative stress alleviation, and neural network reconstruction remains an urgent task. Secondly, limitations in experimental studies hinder the generalizability of results. Most experimental studies rely on animal models, such as rat models of SCI, which, while providing important clues, do not fully replicate the pathological features and

recovery processes of human SCI. Additionally, the lack of standardized experimental designs leads to significant variability between studies. Factors such as acupoint selection, stimulation frequency, treatment duration, and intensity are not uniformly defined, affecting the reproducibility and comparability of results.In clinical research, challenges include small sample sizes, the absence of multicenter validation, and heterogeneity in study designs. Many clinical trials involve limited sample scales, restricting the statistical power of their conclusions. Moreover, different studies employ varying efficacy evaluation standards, particularly in quantifying functional recovery and quality-of-life improvements. The lack of international standards and guidelines for acupuncture clinical applications also poses barriers to its global promotion. To address these challenges, future research on acupuncture in SCI treatment must deepen along multiple dimensions. Firstly, in basic research, multidisciplinary integration should be strengthened. Modern biological technologies such as single-cell sequencing, gene editing, and multi-omics analysis can provide a comprehensive understanding of acupuncture's multi-dimensional mechanisms. Targeting critical processes such as neural repair, inflammation regulation, and neural network reconstruction, future studies could employ genome-wide association studies (GWAS) or fMRI to explore acupuncture's systemic regulatory effects on the nervous system. Secondly, standardizing experimental research is key to improving research quality. Establishing unified experimental design standards, including the selection of animal models, standardized acupuncture protocols, and efficacy evaluation criteria, will enhance the reliability and comparability of results. Additionally, novel models such as organoids or human-like neural network simulations could bridge the gap between animal experiments and human pathophysiology, providing more realistic biological contexts for precision acupuncture research.In clinical research, large-scale, multicenter randomized controlled trials should be promoted, especially to assess acupuncture's effects across different types of SCI patients. Standardized evaluation criteria, such as combining ASIA scores with functional imaging and quality-of-life surveys, are necessary to comprehensively evaluate acupuncture's practical efficacy. Furthermore, international collaboration in acupuncture clinical research is essential for developing standardized treatment protocols and operational guidelines, laying the groundwork for its global application.Lastly, integrating traditional acupuncture with modern technologies will drive its modernization. For example, combining acupuncture with artificial intelligence and big data analysis could enable personalized treatment planning and efficacy prediction. By analyzing large-scale clinical data, optimal acupoint combinations and treatment frequencies for various SCI types could be identified. Intelligent acupuncture devices can also standardize and refine procedures, improving reproducibility and safety.In summary, while acupuncture research for SCI treatment faces many challenges, its potential for development is immense. By deepening basic research, optimizing experimental design, advancing standardized clinical trials, and incorporating modern technologies, acupuncture has the potential to evolve into a scientifically robust modern medical intervention, offering broader hope and more effective treatment options for SCI patients.

6. Conclusion

Acupuncture demonstrates significant potential in promoting functional recovery following SCI through mechanisms such as neural repair, inflammation regulation, oxidative stress alleviation, and neural network reconstruction. Experimental and clinical studies have validated its efficacy, though challenges such as unclear mechanisms and non-standardized designs persist. Future efforts should focus on interdisciplinary research, standardized experimental design, and international clinical validation, leveraging modern technologies to advance the scientific and precise application of acupuncture, ultimately providing more effective treatment options for SCI patients.

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