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REVIEW

Clinical Applications and Potential Mechanism of Cold Acclimation Therapy

Yongxing Wang[1,*], Yajun Wang[1,*], Dezhi Han[2], Weijing Sun[2], Yaqun Qiao[1], Conghui Wang[3], Xu Zhang[1], Jinlong Xu[2]

[1]Department of General Surgery, The 969th Hospital of the Chinese People's Liberation Army Joint Logistics Support Force, Hohhot, Inner Mongolia, 010051, People's Republic of China; [2]Department of Burn and Plastic Surgery, The 969th Hospital of the Chinese People's Liberation Army Joint Logistics Support Force, Hohhot, Inner Mongolia, 010051, People's Republic of China; [3]Clinical Lab, The 969th Hospital of the Chinese People's Liberation Army Joint Logistics Support Force, Hohhot, Inner Mongolia, 010051, People's Republic of China

*These authors contributed equally to this work

Correspondence: Jinlong Xu, Department of Burn and Plastic Surgery, The 969th Hospital of the Chinese People's Liberation Army Joint Logistics Support Force, No. 111 Aimin Road, Hohhot, 010051, People's Republic of China, Tel +8618548164089, Email xujinlong1986228@163.com

Abstract: Cold acclimation therapy has emerged as a notable therapeutic approach with physical therapy and clinical medicine. Driven by the rising demand for effective pain management, sports recovery, and inflammation control, several studies have examined the physiological mechanisms and diverse applications of cold acclimation therapy. Current research shows that cold acclimation therapy can effectively alleviate both acute and chronic pain, promote post-exercise recovery, and mitigate inflammatory responses. Despite its potential, challenges persist in its clinical application, including the determination of precise clinical indications, optimal timing of intervention, and potential adverse effects. This review summarizes the fundamental principles, clinical applications, current research progress, and future potential of cold acclimation therapy, aiming to provide a reference for clinical practice. Furthermore, the future applications of cold acclimation therapy in medical practice is discussed, emphasizing its importance and development prospects in modern healthcare.

Keywords: cold acclimation therapy, inflammation control, pain management, physical therapy, sports recovery

Introduction

Cold acclimation therapy, an innovative therapeutic modality, has been widely applied across various medical disciplines in recent years due to its ability to regulate body surface temperature for therapeutic benefits. The application history of cold therapy can be traced back to ancient times. In ancient Egypt and Greece, there were records of using ice compresses to relieve inflammation and pain. Systematic research on modern cold therapy began at the end of the 19th century. With the development of refrigeration technology, its clinical application gradually became standardized. After the middle of the 20th century, a large number of basic studies revealed that cold therapy exerts the effects of reducing tissue damage and promoting repair through mechanisms such as lowering tissue metabolic rate, constricting blood vessels, and inhibiting the release of inflammatory mediators. Research has shown that cryotherapy can effectively alleviate chronic pain, especially in individuals with rheumatic and degenerative diseases.[1] Additionally, cold acclimation therapy has garnered notable attention in sports medicine, where athletes use cryotherapy after training and competition to accelerate recovery, reduce muscle soreness, and enhance athletic performance.[2]

In the field of sports medicine, studies have confirmed that athletes who undergo whole-body cryotherapy (−110°C to −140°C, for 2–3 minutes) after high-intensity training or competitions can significantly accelerate the relief of muscle soreness by 30%-40%, and also significantly reduce the level of serum creatine kinase, indicating that cryotherapy can effectively alleviate sports-related muscle injuries.[3] A prospective study on professional basketball players showed that local cryotherapy after training could shorten the recovery time of muscle fatigue by 25% and significantly improve the performance score.[4] Currently, approximately 85% of professional sports teams incorporate cryotherapy into their regular

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recovery plans. They use methods such as ice baths and cold compression devices to help athletes shorten the recovery period and reduce the risk of fatigue accumulation.[5] In cases of mandibular third molar extraction, cryotherapy has been found to effectively reduce swelling and pain, with individuals exhibiting significant reduction in swelling by the second postoperative day.[6] Additionally, its efficacy has been documented in pain management following breast-conserving surgery. Studies have indicated that individuals who received cryotherapy reported significantly lower pain scores within 24 hours postoperatively compared to control groups.[7] These findings highlight the potential of cold acclimation therapy as a valuable tool in acute pain management. In the management of chronic diseases, early studies have shown that local cold therapy has a significant improvement effect on joint pain and morning stiffness in patients with rheumatoid arthritis. A randomized controlled trial involving 120 patients demonstrated that 4-week cold therapy on the affected joints could reduce the patient's pain visual analogue scale (VAS) score by 42% and increase joint mobility by 28%.[8] Moreover, cold therapy has shown potential in the treatment of refractory pain conditions such as fibromyalgia syndrome and neuropathic pain. Some studies have indicated that the combination of cold therapy and drug treatment can produce a synergistic effect.[9]

Despite its broad clinical prospects, further research efforts must explore the effects of cold acclimation therapy across diverse conditions and populations. For example, studies on pain management following spinal surgery have shown that individuals receiving cryotherapy exhibited significantly lower pain scores within 48 hours post-surgery compared to the control groups, suggesting the potential value of cryotherapy in early postoperative management.[10] However, variability in individual responses to cryotherapy necessitates additional research to optimize application strategies and tailor treatments to different populations. At present, the standardization level of cold therapy in clinical applications still needs to be improved. Only about 60% of medical institutions have formulated clear operation guidelines for cold therapy.[11]

Whole-body cryotherapy and precise temperature control devices each have their own advantages and disadvantages. Traditional cold therapy is simple to operate, cost-effective, and requires only ice or cold packs, making it suitable for home and primary healthcare settings. It is also safe, with minimal side effects from short-term local application, making it ideal for managing early postoperative swelling.[6] Additionally, it provides immediate pain relief and anti-inflammatory effects by constricting blood vessels and reducing tissue metabolism, effectively alleviating acute inflammation and pain.[1] However, it has some drawbacks: temperature control is not precise, its effect depth is limited, and it primarily provides short-term benefits. Modern cold therapy, on the other hand, offers significant and quantifiable therapeutic effects. Whole-body cryotherapy (−110°C to-140°C) can accelerate muscle recovery by 30%-40% and reduce serum creatine kinase levels.[3,4] It also improves microcirculation and promotes repair through extreme low-temperature stimulation of systemic physiological responses.[8] Furthermore, it has the potential to integrate with medications and physical therapies, enhancing overall effectiveness.[9] However, it is dependent on specialized equipment and is expensive, with a penetration rate of only about 85% in medical institutions.[5,11] Individual responses can vary widely, and some patients may have limited benefits due to poor tolerance to low temperatures, requiring personalized treatment plans.[11] Additionally, there are potential risks and contraindications; extreme low temperatures can trigger cardiovascular stress, posing risks to individuals with hypertension or cold sensitivity.[3,10] In summary, the key differences between traditional cold therapy and modern cold therapy lie in temperature control accuracy and the scope of action. The former is more suitable for rapid intervention of acute and localized symptoms, while the latter achieves systemic repair through systematic cryotherapy exposure. However, it is essential to balance costs and risks. Future research should further address standardized procedures,[11] personalized treatment planning,[12] and long-term safety issues to maximize the clinical value of cryotherapy.

The future of cold acclimation therapy research and application holds significant potential. Advances in technology are expected to diversify the design and functionality of cold acclimation therapies, facilitating integration with other therapeutic modalities such as physical therapy and pharmacological treatments to achieve enhanced therapeutic outcomes. Additionally, as the field of personalized medicine continues to gain prominence, future research is likely to focus on customizing cryotherapy regimens based on the specific conditions of individuals to maximize treatment efficacy and satisfaction.[12] In conclusion, cold acclimation therapy, as an emerging physical therapy modality, offers vast application potential and merits further exploration and integration into clinical practice.

Physiological Mechanisms Underlying Cold Acclimation Therapy

Cold acclimation therapy, as an emerging personal cooling technology, primarily achieves its cooling effects through physical cooling mechanisms and the modulation of physiological responses to temperature. This approach is designed to provide efficient and comfortable temperature regulation, particularly for individuals operating in high-temperature environments, such as firefighters, military personnel, and those engaged in high-intensity activities. The core mechanism of cold acclimation therapy involves an integrated cooling system, which typically uses a circulating coolant to lower the temperature within the garment, thereby reducing the heat load experienced by the individual.

Physical Cooling Mechanism

The physical cooling mechanism underlying cold acclimation therapy is based on the principle of heat exchange. A cooling fluid circulates within the garment, absorbing excess heat generated by the user's body and dissipating it to the surrounding environment. This cooling method effectively lowers core body temperature and mitigates physiological stress caused by high-temperature environments. For example, a study demonstrated that firefighters wearing cooling suits in high-temperature environments exhibited significantly lower core body temperatures during firefighting tasks compared to the control group without cooling suits. These findings highlighted the efficacy of cooling suits in reducing high environmental temperatures.[13] Additionally, the design of the cooling suit considers breathability and ergonomic comfort, ensuring optimal cooling effects without compromising mobility or user comfort.

Effects of Temperature on Physiological Responses

Temperature fluctuations exert a significant impact on physiological responses, especially in high-temperature environments where the human body is subjected to considerable stress. Prior studies have shown that elevated temperatures induce adaptive physiological responses such as increased heart rate, elevated blood pressure, and increased sweating. However, exposure to extreme heat can impair cognitive function and delayed response times, leading to reduced overall performance.[14] Cold acclimation therapy, by effectively lowering body temperature, has been shown to enhance both cognitive performance and reaction speed. Research has demonstrated that individuals using cooling suits in high-temperature environments exhibited significantly shorter response times in cognitive tasks compared to those without these cooling suits. These findings indicate the potential application of cooling suits in improving cognitive function.[15] Therefore, cold acclimation therapy not only provides effective physical cooling but also enhances cognitive and physiological performance by regulating body temperature.

Application of Cold Acclimation Therapy in Pain Management

Relief of Acute Pain

Cryotherapy, a form of cold acclimation therapy, and a prominent non-pharmacological approach to pain management, has demonstrated significant efficacy in alleviating acute pain. Studies have demonstrated that cryotherapy can effectively alleviate postoperative pain, particularly in pain management following chest tube removal. Systematic reviews and network meta-analyses have shown that cryotherapy significantly reduces pain levels both immediately after tube removal and 10 to 20 minutes post-removal, with standardized mean differences of −1.84 and −1.96, respectively. These results indicate the potential of cryotherapy in the management of acute pain.[12] Additionally, in individuals undergoing breast-conserving surgery, those receiving cryotherapy reported significantly lower pain levels within the first 24 hours post-surgery compared to control groups, along with improved recovery quality. These outcomes suggest that cryotherapy not only alleviates pain but also improves the overall recovery experience.[7] Therefore, as a simple, effective, and side-effect-free pain management method, cryotherapy warrants broader adoption and integration into clinical practice.

Treatment Effects on Chronic Pain

Cryotherapy has shown promise as an adjunctive therapy for managing chronic pain. Studies have indicated that cryotherapy can serve as an adjunctive therapy to help alleviate symptoms in individuals with chronic pain. For individuals with chronic neck pain, combining cryotherapy with pain neuroscience education has demonstrated better

results, including significantly reducing the Pain Disability Index and pain catastrophizing scores.[16] Additionally, cryotherapy has demonstrated therapeutic potential in managing chronic lower back pain, especially when combined with other therapeutic modalities. This combination therapy has been shown to improve quality of life and functional status in affected individuals.[17] Although the specific mechanisms of cryotherapy in chronic pain management require further research, existing evidence supports its role as a valuable component of a comprehensive management plan for chronic pain, particularly in multimodal treatment strategies. By improving pain management and overall quality of life, cryotherapy represents a potential clinical option for the treatment of chronic pain.[18]

Role of Cold Acclimation in Sports Injury Recovery

Recovery from Muscle Fatigue After Exercise

Cold acclimation therapy, specifically cryotherapy plays a significant role in promoting recovery from muscle fatigue following physical activity. Numerous studies have demonstrated that cryotherapy can effectively reduce muscle damage and fatigue, promoting recovery. Commonly used methods, such as cold-water immersion and whole-body cryotherapy (WBC), mitigate exercise-induced muscle pain and fatigue by lowering muscle temperature and modulating inflammatory responses. For example, research has demonstrated that cold water immersion significantly reduces muscle soreness within 24 hours following exercise and, in some cases, improves exercise performance.[19] Furthermore, cryotherapy accelerates recovery by inhibiting inflammatory mediators in muscles, such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α).[20] The efficacy of cryotherapy may vary based on individual characteristics and the type of physical activity, emphasizing the importance of selecting the appropriate method and timing of its application. Studies have indicated that administering WBC within one hour following exercise is more effective in restoring muscle strength than delayed cryotherapy.[21] In summary, cold acclimation therapy promotes recovery from muscle fatigue through various mechanisms, establishing its value as an essential tool in sports medicine and athletic recovery protocols.

Prevention and Treatment of Sports Injuries

Cold acclimation therapy has proven effective in the prevention and treatment of sports injuries. Cryotherapy can reduce the incidence of sports injuries by lowering local temperature, slowing metabolism, and inhibiting inflammatory responses. For example, cold water immersion and ice packs are widely used in the initial treatment of acute sports injuries, effectively reducing swelling and pain.[22] Studies have demonstrated that timely application of cryotherapy reduces the severity of muscle damage and promotes tissue repair following injury.[23] Additionally, cryotherapy aids in recovery following intense training sessions, reducing the risk of injuries caused by overtraining.[24] However, despite the significant benefits of cryotherapy in the treatment of acute injuries, its efficacy in managing chronic injuries remains an area requiring further research. Prolonged or improper application of cryotherapy may adversely impact muscle adaptability, potentially affecting strength and endurance gains.[25] To optimize outcomes in the prevention and treatment of sports injuries, the application of cold acclimation therapy should be customized to specific situations, with meticulous consideration of the timing and frequency of therapy.

Application of Cold Acclimation Therapy in Inflammation Control

Physiological Mechanisms of Inflammatory Responses

Inflammatory responses are protective physiological processes initiated by the body in response to injury or infection, involving complex interactions between multiple cells and molecular signaling pathways. The inflammatory process begins with the activation of immune cells such as macrophages and neutrophils, which migrate to the affected site or pathogen invasion. These cells release cytokines such as interleukin (IL)-1, IL-6, and TNF-α, to promote vasodilatation and increase vascular permeability. This mechanism facilitates the delivery of immune cells and nutrients to the damaged area.[26] However, prolonged inflammation may lead to tissue damage and contribute to chronic disease development. Therefore, to counterbalance excessive inflammation, the body employs mechanisms, such as the activity of regulatory T cells, which suppress excessive immune reactions and maintain homeostasis.[27] A detailed understanding of these physiological mechanisms is crucial for developing new anti-inflammatory treatment strategies.

Effects of Cold Acclimation Therapy on Inflammation

Cold acclimation therapy has demonstrated significant promise in managing inflammatory conditions in recent years. Studies indicate that cryotherapy can slow down the inflammatory response by lowering local temperature, reducing swelling and pain. For example, research has demonstrated that cryotherapy significantly reduced ear swelling and eosinophil infiltration in a trimellitic anhydride-induced skin inflammation model, along with a reduction in serum IgE levels and Th2 cytokine release, particularly IL-4 and IL-5, which play a key role in allergic inflammation.[21,28] Cryotherapy has been found to enhance recovery from exercise-induced inflammation. Studies suggest that local cryotherapy supports immune regulation by enhancing the mobilization of CD8+ T cells and natural killer cells.[29] These findings suggest that cold acclimation therapy not only alleviates acute inflammation but may also play a crucial role in managing chronic inflammation, particularly in the fields of sports medicine and rehabilitation.[23] As ongoing research into the underlying mechanisms of cryotherapy continues, the potential of cold acclimation therapy in clinical applications is expected to expand.

Comparison with Heat Therapy

Comparison of Mechanism of Action

Cold adaptation therapy involves using low temperatures to constrict local blood vessels, thereby reducing tissue metabolism and nerve conduction speed, and inhibiting the release of inflammatory mediators such as prostaglandins, which helps reduce swelling and pain. Heat adaptation therapy uses heat to dilate blood vessels, increase local blood flow, promote the clearance of metabolic waste and tissue repair, and relieve stiffness by relaxing muscles and connective tissues.

Indications and Efficacy Comparison

In the management of acute injuries and postoperative care, cold therapy is highly effective during the acute inflammatory phase (such as the first 48 hours). For instance, cold therapy after mandibular surgery can reduce swelling by over 30%, whereas heat therapy might exacerbate edema in the acute phase. Heat therapy is more suitable for the subacute or chronic stages (after 72 hours post-surgery), as it promotes blood circulation and accelerates wound healing. In the treatment of chronic pain and muscle recovery, cold therapy can achieve a 42% reduction in joint pain for patients with rheumatoid arthritis, while heat therapy provides similar pain relief for chronic back pain but excels in improving joint mobility. In sports medicine, cold therapy (such as whole-body cryotherapy) can shorten muscle recovery time by 25–40%, while heat therapy (such as infrared sauna) enhances long-term flexibility by reducing muscle adhesion.

Comparison of Risks and Contraindications of the Two Treatments

Extreme cold (−100°C) may cause frostbite or cardiovascular stress, and patients with hypertension should use it with caution; short-term use (<20 minutes) is safer. Excessive heat exposure may cause burns or increase the risk of bleeding, and it is not suitable for open wounds or infected areas.

Joint Application Potential

Studies have shown that alternating cold and heat therapy (contrast bath) can combine the advantages of both: cold therapy reduces acute inflammation, and heat therapy promotes later repair. For example, in sports recovery, alternating cold and heat can increase muscle function recovery efficiency by 15–20%.

Precautions and Potential Risks of Cold Acclimation Therapy

Contraindications of Cold Acclimation Therapy

Cold acclimation therapy has specific clinical applications; yet it is associated with certain contraindications that must be considered before its implementation. Individuals with cardiovascular conditions, especially those with heart failure or severe hypertension, are at an elevated risk of adverse effects due to the potential blood pressure fluctuations and increased cardiac workload. Consequently, cold acclimation therapy should be administered cautiously. Similarly,

individuals with diabetes, especially those with neuropathy or impaired peripheral circulation, are at an increased risk of localized tissue ischemia or frostbite when exposed to cold environments.[30] Moreover, pregnant women are advised against cold acclimation therapy, as exposure to low temperatures may have adverse effects on the fetus. It is essential for healthcare providers to conduct a comprehensive assessment of the medical history and overall health status of an individual to identify any aforementioned contraindications prior to initiating cold acclimation therapy, thereby mitigating potential risks.

Potential Side Effects

Although cold acclimation therapy is effective in regulating body temperature, it is associated with potential side effects. Common reported adverse effects include skin irritation and allergic reactions, particularly with prolonged exposure, which may manifest as skin redness, swelling, and itching. Inappropriate or extended use of cold acclimation therapy may induce hypothermia, posing significant risks, especially for individuals with specific pre-disposing physical conditions.[31] Cold acclimation may also affect blood circulation, potentially causing localized numbness or tingling sensations, particularly when cooling intensity is not appropriately adjusted. To minimize these side effects, regular monitoring of body temperature and skin condition is recommended during cold acclimation therapy. Tailoring the duration and intensity of cooling according to the individual's specific condition can ensure safety and effective treatment outcomes.

Conclusion

Cold acclimation therapy, an emerging modality in physical therapy, has demonstrated significant potential in areas such as pain management, recovery from sports injuries, and inflammation control in recent years. Current research underscores its effectiveness in alleviating pain, enhancing post-exercise recovery, and mitigating inflammation, providing a solid foundation for its integration into clinical practice. However, despite the existing evidence supporting its efficacy, further high-quality randomized controlled trials are necessary to further validate the clinical efficacy and safety of this therapeutic modality.

It is important to recognize that the study of cold acclimation therapy remains in its early stages. Several studies are limited by small sample sizes and methodological shortcomings, which may impact the reliability and generalizability of their findings. Therefore, future research should focus on larger, more diverse sample populations and improved study designs to comprehensively assess the clinical value and applicability of cold acclimation therapy.

As advancements in technology continue to emerge, the design and application of cold acclimation therapies are constantly evolving. The introduction of new materials and the development of smart systems are expected to enhance the adaptability and effectiveness of cold acclimation therapies. It is imperative for researchers and clinicians to remain updated on these developments to maximize the potential of cold acclimation therapy in clinical practice.

In conclusion, cold acclimation therapy holds considerable promise for widespread application in clinical settings. However, its potential can only be realized through rigorous scientific research that produces consistent and reliable evidence. By addressing current research gaps, future studies can support the integration of cold acclimation therapy in clinical practice, and provide individuals with more effective treatment options.

Abbreviations

WBC, Whole-body cryotherapy; IL-6, Interleukin-6; TNF-α, Tumor necrosis factor-alpha.

Data Sharing Statement

All data generated or analyzed during this study are included in this article. Further enquiries can be directed to the corresponding author.

Ethics Approval and Consent to Participate

The study was a literature review and did not involve human or animal experimenters. This study was conducted with approval from the Ethics Committee of The 969th Hospital of the Chinese People's Liberation Army Joint Logistics Support Force (Approval date: 2025.1.16).

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