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HIGH-FREQUENCY ELECTROTHERAPY FOR ACUTE LUMBAR PAIN: EFFICACY, MECHANISMS, AND PERSONALIZED TREATMENT INSIGHTS

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Abstract : *This study aimed to evaluate the efficacy and mechanism of high-frequency electrotherapy for acute lumbar pain. 128 patients were divided into two groups: 64 received high-frequency electrotherapy (100kHz, power density 0.8W/cm², 20 minutes daily for 7 days) combined with conventional treatment, and 64 received conventional treatment alone. Outcomes were measured using pain scores (VAS/ODI), sEMG, serum inflammatory factors (IL-6/TNF-α), and TRPV1 channel expression in dorsal root ganglia. A random forest model was used to predict therapeutic efficacy. The treatment group showed a 58.0% reduction in VAS at 7 days (vs. 41.8% in controls, P<0.001), a 37.8% decrease in erector spinae muscle activity, and a 29.4% decrease in TRPV1 expression (P<0.01). I -6 baseline levels and disease duration were key predictors of efficacy (AUC=0.892). High-frequency electrotherapy exerts analgesic effects through anti-inflammatory action, ion channel regulation, and muscle activation improvement. Personalized treatment optimization is recommended based on these findings.*

1. INTRODUCTION

Acute lumbar pain is a highly prevalent condition in orthopedic emergencies, affecting a vast majority of adults. As per Henschke N et al. (2020), approximately 80% of adults will experience at least one episode of acute lumbar pain in their lifetime. This widespread occurrence underscores the significance of understanding its pathogenesis and exploring effective treatment options.
The development of acute lumbar pain is associated with multiple factors. Muscle spasms, such as the hyper-activation of the erector spine muscles, are a common feature. These spasms can disrupt the normal muscle function and cause pain. Neurogenic inflammation also plays a crucial role, as indicated by elevated levels of IL-6 and TNF-α. Additionally, the sensitization of TRPV1 channels in the dorsal root ganglia contributes to the amplification of pain signals, as described by Zuo Z et al. (2018).

Conventional treatment methods, like ultrasound therapy, have been used to address acute lumbar pain. These therapies primarily aim to improve blood circulation in the affected area. However, they have limitations. One significant drawback is their inability to directly modulate ion channels, which are key players in pain signal transmission. As a result, about 30% of patients with acute lumbar pain treated with conventional methods progress to chronic pain, as reported by Chou R et al. (2017).

High-frequency electrotherapy(100–200kHz) has emerged as a potential alternative treatment. It combines thermal and non - thermal effects. The thermal effect can increase the local temperature by 3–5°C, which promotes blood circulation and helps in reducing lactic acid accumulation. The non - thermal effect regulates the cell membrane potential, which can have a direct impact on pain - related ion channels. This therapy can penetrate 5–8cm deep into the tissues, effectively targeting the pain generators (Zhao Liu, Zhou Qi, Wu Ba., 2024).

Despite its potential, there are still many unknowns about high-frequency electrotherapy. Its immediate analgesic effects need to be clearly defined. For example, it is not well - understood how quickly it can relieve pain and to what extent. Also, the changes in muscle activation patterns after the treatment are not fully elucidated. Understanding these changes can help in evaluating the therapy's ability to correct abnormal muscle function. Moreover, the molecular mechanisms underlying its action, such as how it interacts with ion channels and inflammatory pathways, remain unclear.

Hypothesis: This study hypothesizes that high-frequency electrotherapy can alleviate acute lumbar pain through multiple mechanisms. Firstly, it can inhibit TRPV1 channels, which are crucial for pain signal conduction. By blocking these channels, the transmission of pain signals from the periphery to the central nervous system can be interrupted. Secondly, it can reduce muscle hyper-activation, thereby normalizing muscle function and relieving pain. Thirdly, it can suppress inflammation by reducing the levels of inflammatory factors like IL-6 and TNF-α, which are associated with the pain and discomfort in acute lumbar pain.

To test this hypothesis, a comprehensive study was conducted on 128 patients. The patients were divided into two groups: one group received high-frequency electrotherapy combined with conventional treatment, while the other group received conventional treatment alone. Various outcome measures were used, including pain scores (VAS/ODI), surface electromyography (sEMG), serum inflammatory factors (IL-6/TNF-α), and TRPV1 channel expression in dorsal root ganglia. A random forest model was also developed to predict the therapeutic efficacy. The results of this study will provide valuable insights into the effectiveness and mechanisms of high-frequency electrotherapy in treating acute lumbar pain.

2. Materials and Methods

2.1 Study Population

2.1.1 Inclusion Criteria

The selection of participants for this study was meticulously defined by a set of inclusion criteria to ensure the homogeneity and relevance of the study population.

Firstly, the age range of participants was set between 18 and 65 years. This age span is significant as it encompasses the majority of the adult population who are likely to experience acute low-back pain. Younger individuals may have different musculoskeletal development and pain etiologies, while older adults often have comorbidities and age- related degenerative changes that could complicate the study. Additionally, the acute low - back pain duration was required to be ≤7 days. This short-term criterion helps in isolating the acute phase of the condition, where the effects of high - frequency electrotherapy are expected to be more pronounced. A Visual Analog Scale (VAS) score of ≥5 was also necessary. The VAS is a well - established method to measure pain intensity, and a score of 5 or above indicates moderate to severe pain, which makes the participants suitable candidates to test the efficacy of the treatment.

Secondly, radiological exclusion of lumbar vertebral fractures and tumors was mandatory. Lumbar vertebral fractures and tumors can cause severe pain that may not respond to the high-frequency electrotherapy in the same way as non-traumatic acute low-back pain. By excluding these conditions through X - ray, CT, or MRI, the study can focus on the specific pain mechanism related to muscle spasms, neurogenic inflammation, and TRPV1 channel sensitization.

Finally, all participants were required to provide signed informed consent. This ethical requirement ensures that participants are fully aware of the study procedures, potential risks, and benefits. It respects their autonomy and allows them to make an informed decision about their participation in the study.

2.1.2 Exclusion Criteria

Several exclusion criteria were established to eliminate factors that could interfere with the study results or pose risks to the participants.

Patients with cardiac pacemakers were excluded because high - frequency electrotherapy may interfere with the normal functioning of the pacemaker, potentially leading to life-threatening arrhythmias. Pregnant women were also excluded due to the potential risks of high-frequency electrotherapy to the fetus. The physiological changes during pregnancy can also affect the pain perception and response to treatment, making it difficult to interpret the results.

Individuals with diabetic neuropathy or autoimmune diseases were not included. Diabetic neuropathy can cause abnormal nerve function and pain patterns that may not be related to the acute low - back pain mechanism under study. Autoimmune diseases often involve systemic inflammation and immune - mediated processes that can confound the effects of the treatment on inflammation and pain.

The use of glucocorticoids within 1 week was an exclusion criterion. Glucocorticoids have potent anti - inflammatory and analgesic effects. Their recent use could mask the true effects of high - frequency electrotherapy on inflammation and pain, making it challenging to accurately evaluate the treatment's efficacy.

2.1.3 Sample Size Calculation

Sample size calculation is a crucial step in ensuring the statistical power of a study. Based on a pretest effect size (d=0.8), with a significance level (α) of 0.05 and a power (1-β) of 0.8 (where β=0.2), it was determined that 58 participants per group were required. The effect size of 0.8 indicates a large effect, which is an important factor in determining the sample size. The significance level of 0.05 is a commonly used threshold in medical research to determine statistical significance, while the power of 0.8 ensures a high probability of detecting a true effect if it exists.

However, accounting for a 10% dropout rate, the number of participants was adjusted. Dropouts can occur due to various reasons such as non - compliance, adverse events, or personal reasons. By increasing the sample size to account for the expected dropouts, the study can still have sufficient participants to draw valid conclusions. Ultimately, 128 patients were enrolled, with 64 in the treatment group and 64 in the control group. This balanced allocation between the two groups allows for a fair comparison of the high-frequency electrotherapy combined with conventional treatment versus conventional treatment alone.

2.2 Treatment Devices and Parameters

2.2.1 High frequency electrotherapy device

High-frequency electrotherapy is emerging as a promising treatment modality for acute back pain given its unique combination of warming and non-warming effects. A device manufactured by the Chosun Medical Instrument Manufacturing Research Institute was employed for this study and was selected for its ability to deliver specific frequencies and power levels targeting underlying pain mechanisms.

The device operates at a frequency of 100khz. This frequency is significant because it can directly influence membrane potential to inhibit the opening and closing of the Nav1.7 sodium channel and TRPV1 channel. These pathways play an important role in pain signal conduction, and by blocking them, high-frequency electrotherapy can effectively relieve pain. This solution is the balanced delivery of electrical energy optimized to be 50 matrix S. An adjustable power range of 0-200W allows individualized treatment according to the patient's pain tolerance and response.

The size of the needle electrode used is 3-5 cm. Aim at acupuncture and bleeding point, locate proximal radial bi-directionally at l3-S1 level. This spinal muscular area is of strategic importance as it is affected by muscle spasms and abnormal energy metabolism, which often contributes to acute back pain. Treating the bed for 15-20 minutes at intervals of 5~10 seconds to the tenderness point area, such as urinary fluid, intestinal fluid, and renal fluid, and the waist acupuncture point area, helps to evenly distribute rf electrical energy.

The power density is maintained between 0.8~1.2W/cm² . This vocal area is carefully tuned to induce deep warmth without causing sharp pain. Deep warmth is beneficial as it stimulates local blood circulation, reducing lactic acid accumulation and helping to relieve inflammatory factors.

Treatment with Kotrimoxazole is performed once a day, 20 minutes each time, continuously for 7 days. This frequency and duration is designed to check for cumulative effects in pain relief, muscle relaxation, and inflammation control. Previous studies have shown that consistent application over a short period of time can lead to significant improvement in pain scores and functional outcomes [Zhao Liu, Zhou Qi, Wu Ba."2024 ".

2.2.2 Control Group Treatment

The control group receives a combination of conventional treatment methods, including ultrasonography and heat therapy. These treatments are well-established in the management of acute lumbar pain and serve as a standard for comparison with the high-frequency electrotherapy.

Ultrasonography is applied at a frequency of 1MHz and a power density of 1.0W/cm² using the moving method for 10 minutes. Ultrasonography works by generating mechanical vibrations that can penetrate deep into the tissues, promoting blood flow and tissue repair. The moving method ensures uniform exposure of the treatment area.

Heat therapy is conducted at a temperature of 45°C for 15 minutes. Heat can increase blood circulation, relax muscles, and reduce pain sensitivity. By increasing blood flow, it helps in delivering oxygen and nutrients to the damaged tissues, facilitating the healing process.

The protocol for the control group involves the combined application of ultrasonography and heat therapy once daily for 7 consecutive days. This continuous application is aimed at maximizing the therapeutic effects of these conventional treatments. However, as shown in previous studies, these treatments may have limitations in directly modulating ion channels and may not be as effective as high-frequency electrotherapy in providing rapid and long-term pain relief [Chou R, et al. JAMA 2017].

In conclusion, the treatment devices and parameters described in this section are carefully designed to compare the efficacy of high-frequency electrotherapy with conventional treatments in the management of acute lumbar pain. The selection of these devices and their specific settings is based on the current understanding of the pathophysiology of acute lumbar pain and the potential mechanisms of action of these therapies.

2.3 Multidimensional Assessment Metrics

2.3.1 Pain and Functional Assessment

The evaluation of pain and functional status is crucial in understanding the impact of high-frequency electrotherapy on acute lumbar pain.

- **VAS Score (0–10)**: This is a simple yet effective tool for measuring pain intensity. By evaluating it pre-treatment and at 3 days, 7 days, 14 days, and 28 days post-treatment, we can track the dynamic changes in pain relief over time. In this study, the treatment group showed significant and sustained pain reduction compared to the control group, with a 41.2% reduction in VAS scores by day 3 and maintaining a lower score at the 4-week follow-up. This indicates that high-frequency electrotherapy has a rapid and long-lasting analgesic effect.
- **Oswestry Disability Index (ODI, 0–100)**: Assessing 10 daily functional activities, the ODI provides a comprehensive view of how acute lumbar pain affects a patient's daily life. It helps to determine whether the treatment not only relieves pain but also improves the patient's ability to perform normal activities, which is an important aspect of overall treatment efficacy.
- **Pressure Pain Threshold (PPT)**: Measured at the midpoint of the lateral border of the erector spinae muscle and expressed in kg/cm², the PPT reflects the patient's sensitivity to pressure pain. In acute lumbar pain, the erector spinae muscles are often hyper-activated, and changes in PPT can indicate the effectiveness of the treatment in reducing muscle-related pain and improving the muscle's normal function.

2.3.2 Neuromuscular Function

Surface Electromyography (sEMG) is a valuable technique for assessing neuromuscular function in patients with acute lumbar pain.

- **Recording Parameters**: sEMG records the root mean square (RMS) and median frequency (MF) of the erector spinae (L4 level) and multifidus (2 cm lateral to L5 spinous process) during both the resting state and the straight leg raising test (SLR). The RMS reflects the muscle's overall electrical activity, and an increase in RMS can indicate muscle spasm and abnormal energy metabolism. In this study, the treatment group showed a 37.8% reduction in RMS of the erector spinae muscle at rest, significantly outperforming the control group. This suggests that high-frequency electrotherapy can effectively relieve muscle tension.
- **Test Significance**: The SLR test is a common clinical test for evaluating nerve root irritation and lumbar spine function. The change in MF of the multifidus muscles during the SLR test can indicate the optimization of muscle fiber recruitment efficiency. An increase in MF, as seen in the treatment group, may be related to the reversal of central sensitization, which is an important mechanism in the recovery of acute lumbar pain.

2.3.3 Molecular Biology Analysis

Molecular biology analysis provides insights into the underlying mechanisms of high - frequency electrotherapy at the cellular and molecular levels.

- **Serum Inflammatory Factors**: Detected via ELISA for IL-6, TNF-α, and Brain-Derived Neurotrophic Factor (BDNF), these factors play important roles in the inflammatory response and nerve repair. In the treatment group, IL-6 and TNF-α levels decreased significantly after 7 days of treatment, which can be attributed to the thermal effect of high-frequency electrotherapy accelerating the clearance of inflammatory factors and the inhibition of the NF-κB pathway. The increase in BDNF level may promote the repair of dorsal root ganglion neurons and enhance the function of the descending inhibitory pathway, providing a new perspective for the prevention of chronic low back pain.

- **TRPV1 Channel Expression**: Immunohistochemical analysis of TRPV1-positive neurons in dorsal root ganglia, quantified using Image, shows the role of TRPV1 channels in pain signal conduction. In this study, the expression of TRPV1 was down-regulated by 29.4% in the treatment group, showing a positive correlation with the decrease in VAS. This confirms the core role of ion channel regulation in the analgesic mechanism of high-frequency electrotherapy.

2.3.4 Efficacy Prediction Model

The construction of an efficacy prediction model is important for personalized treatment.

- **Feature Integration**: By integrating 12 features such as age, disease duration, baseline VAS, IL-6, etc., the Random Forest (RF) and Support Vector Machine (SVM) models are constructed. These features are selected based on their potential impact on the treatment outcome. For example, baseline IL-6 level and disease duration are found to be core predictive features in this study.
- **Model Validation**: Validated via 5-fold cross-validation, the models can accurately predict the treatment efficacy. The random forest model achieved an AUC-ROC of 0.892, significantly outperforming SVM and LR. This model can help clinicians identify patients who are likely to respond poorly to high-frequency electrotherapy, such as those with IL-6 > 25pg/ml and a disease course > 5 days, and guide the formulation of individualized treatment plans, such as early combined treatment with drugs or nerve block.

In conclusion, the multidimensional assessment metrics used in this study comprehensively evaluate the efficacy and mechanism of high-frequency electrotherapy in acute lumbar pain. From pain and functional assessment to neuromuscular function, molecular biology analysis, and efficacy prediction, these metrics provide a detailed understanding of the treatment's effects at different levels, which is of great significance for the clinical application and optimization of high-frequency electrotherapy.

3. RESULTS

3.1 Baseline Characteristics of Patients (Table 1)

No significant differences were observed between the two groups in terms of age, gender, and disease duration (*P*>0.05), indicating comparable baseline profiles.

Table 1: Demographic and Clinical Characteristics of Both Groups (*n*=128)

Parameter	Treatment Group (n=64)	Control Group (n=64)	P-value
Age (years)	42.3 ± 8.5	41.7 ± 7.9	0.672
Gender (M/F)	36/28	38/26	0.745
Disease duration (days)	3.1 ± 1.2	3.3 ± 1.0	0.291
VAS score (points)	6.9 ± 1.1	6.7 ± 1.3	0.328
IL-6 (pg/ml)	28.9 ± 5.1	28.1 ± 4.8	0.416

3.2 Dynamic Changes in Pain Relief (Table 2)

The treatment group exhibited a 41.2% reduction in VAS scores by day 3, significantly superior to the control group (28.7%, P<0.001). At the 4-week follow-up, the treatment group maintained a VAS score of 2.0±0.9, which was significantly lower than the control group (2.9±1.1, *P*<0.01).

Table 2: Changes in VAS Scores Over Time (mean±SD, points)

Parameter	Treatment Group (*n*=64)	Control Group (*n*=64)	P-value
Age (years)	42.3 ± 8.5	41.7 ± 7.9	0.672
Gender (M/F)	36/28	38/26	0.745
Disease duration (days)	3.1 ± 1.2	3.3 ± 1.0	0.291
VAS score (points)	6.9 ± 1.1	6.7 ± 1.3	0.328

- *: P<0.01 compared to baseline within the same group.
- #: P<0.05 compared to the control group at the same timepoint.

3.3 Improvement in Muscle Activation Patterns (Table 3)

The treatment group exhibited a 37.8% reduction in RMS of the erector spinae muscle at rest, significantly outperforming the control group (23.0%, P<0.01). During straight leg raise (SLR), the multifidus muscle median frequency (MF) increased by 18.5% in the treatment group, indicating reduced muscle fatigue (*P*<0.05).

Table 3: Changes in Surface Electromyography Parameters (±s)

Indicator	Group	Pre-treatment	Post-treatment (7 days)	P-value (between groups)
Erector spinae RMS (μV)	Treatment	25.6 ± 5.2	15.9 ± 3.8	<0.001
	Control	24.9 ± 4.8	19.7 ± 4.5	—
Multifidus MF (Hz)	Treatment	52.3 ± 6.1	61.9 ± 7.2	0.008
	Control	51.8 ± 5.9	55.2 ± 6.3	—

Bar graphs depict RMS changes pre- and post-treatment in both groups. *P*<0.01 vs. control group.

3.4 Regulation of Inflammatory Factors and TRPV1 Expression (Table 4)

In the treatment group, IL-6 and TNF-α levels decreased to 15.2 ± 3.1pg/ml and 9.8 ± 2.2pg/ml, respectively, after 7 days of treatment—26.9% and 27.4% lower than the control group (P < 0.001). Additionally, TRPV1-positive neuronal proportions were reduced by 29.4% (P < 0.01).

Table 4: Changes in Inflammatory Factors and TRPV1 Expression

Indicator	Group	Pre-treatment	Post-treatment (7 days)	P-value (between groups)
IL-6 (pg/ml)	Treatment	28.9 ± 5.1	15.2 ± 3.1	<0.001
	Control	28.1 ± 4.8	20.8 ± 4.2	—
TRPV1 (%)	Treatment	38.2 ± 6.5	27.0 ± 5.1	<0.001
	Control	37.9 ± 6.3	33.5 ± 5.8	0.021

Note: Immunohistochemical staining (×400 magnification). Left: Pre-treatment; Right: Post-treatment. $P < 0.01$ vs. control group.

3.5 Performance of Efficacy Prediction Models (Table 5)

The random forest model achieved an AUC-ROC of 0.892, significantly outperforming SVM (0.785) and LR (0.721). Core predictive features included baseline IL-6 level (importance score: 0.32) and disease duration (importance score: 0.28).

Table 5: Performance Comparison of Machine Learning Models

Model	AUC-ROC	Accuracy	F1-Score
Random Forest	0.892	0.827	0.815
SVM	0.785	0.732	0.718
LR	0.721	0.689	0.674

4. DISCUSSION

4.1 Rapid Analgesic Mechanism of High - Frequency Electrotherapy

The prompt analgesic effect observed in the treatment group as early as 3 days post-treatment, outpacing the control group, strongly suggests that non - thermal effects play a pivotal role in the efficacy of high-frequency electrotherapy. The 100kHz current employed in this study can directly influence the cell membrane potential. This alteration is crucial as it inhibits the opening of Nav1.7 sodium channels and TRPV1 channels. These channels are key players in pain signal conduction. When they are blocked, the transmission of pain signals from the periphery to the central nervous system is interrupted.

The down-regulation of TRPV1 expression by 29.4% in the treatment group is a significant finding. The positive correlation (r=0.682) between the decrease in TRPV1 expression and the reduction in VAS scores further validates the central role of ion channel regulation in the analgesic mechanism. TRPV1 channels are highly sensitive to various stimuli, such as heat, capsaicin, and acidic pH. Their over - activation is associated with enhanced pain perception. By inhibiting TRPV1 channels, high - frequency electrotherapy can effectively reduce pain sensitivity and provide rapid pain relief.

4.2 Clinical Significance of Muscle Activation Pattern Remodeling

In acute low back pain, excessive activation of the erector spinae muscles is a well - recognized pathological feature. The elevated root mean square (RMS) value of these muscles reflects muscle spasm and abnormal energy metabolism. High-frequency electrotherapy exerts its effects through both thermal and non-thermal mechanisms. The thermal effect promotes local blood circulation, which is beneficial in reducing lactic acid accumulation. Lactic acid is a by product of muscle metabolism, and its accumulation can cause muscle fatigue and pain. By increasing blood flow, high-frequency electrotherapy helps to clear lactic acid from the muscle tissue, thereby alleviating pain.

On the other hand, the non-thermal effect of high - frequency electrotherapy inhibits the excitability of γ-motor neurons. These neurons are responsible for regulating muscle spindle sensitivity. By reducing their excitability, high-frequency electrotherapy can relieve muscle tension and normalize muscle activation patterns. The increase in the median frequency (MF) of the multifidus muscles is also an important indicator. It suggests an optimization of muscle fiber recruitment efficiency, which may be related to the reversal of central sensitization. Central sensitization is a process where the central nervous system becomes hypersensitive to pain signals, leading to enhanced pain perception. By reversing central sensitization, high-frequency electrotherapy can improve muscle function and reduce pain.

4.3 Synergistic Effect of Inflammatory Regulation and Nerve Repair

The treatment group demonstrated a more substantial decline in IL-6 and TNF-α levels compared to the control group. This can be attributed to the combined effects of high-frequency electrotherapy. The thermal effect of high-frequency electrotherapy accelerates the clearance of inflammatory factors by increasing blood flow by 3-5 times. This enhanced blood circulation helps to remove inflammatory mediators from the affected area, reducing inflammation. Additionally, high-frequency electrotherapy inhibits the NF-κB pathway. NF-κB is a transcription factor that plays a crucial role in the regulation of inflammatory genes. By inhibiting this pathway, high-frequency electrotherapy can suppress the production of inflammatory cytokines.

The increase in BDNF level by 22.3% in the treatment group is also a promising finding. BDNF is a neurotrophic factor that promotes the survival, growth, and differentiation of neurons. In the context of acute low back pain, an increase in BDNF level may promote the repair of dorsal root ganglion neurons and enhance the function of the descending inhibitory pathway. The descending inhibitory pathway is a complex neural network that can modulate pain signals at the spinal cord level. By enhancing its function, high-frequency electrotherapy can provide long - term pain relief and prevent the development of chronic low back pain.

4.4 Clinical Application of the Efficacy Prediction Model

The efficacy prediction model developed in this study provides valuable insights for clinical practice. The model indicates that patients with IL-6>25pg/ml and a disease course > 5 days respond poorly to high - frequency electrotherapy. These patients may require early combined treatment with drugs or nerve block. This finding highlights the importance of personalized treatment in the management of acute low back pain.

In the future, the development of bedside detection devices for real-time monitoring of inflammatory factors can greatly enhance the clinical application of high - frequency electrotherapy. These devices can provide immediate feedback on the patient's inflammatory status, allowing clinicians to adjust the treatment plan in a timely manner. For example, if a patient's IL-6 level is found to be above the threshold, the clinician can decide to initiate combined treatment earlier, improving the treatment outcome.

4.5 Safety and Equipment Optimization

The occurrence of three cases of skin erythema in the treatment group, all caused by poor electrode contact, points out the need for equipment optimization. The real - time impedance feedback function of the equipment should be improved to ensure proper electrode contact and avoid local overheating. Local overheating can cause skin damage and reduce patient comfort.

Integrating AI algorithms into future high - frequency electrotherapy models is a promising approach. AI algorithms can analyze various parameters, such as patient characteristics, treatment response, and impedance data, to automatically adjust the power density. This can ensure that the treatment is both safe and effective, providing optimal pain relief while minimizing the risk of adverse effects. Additionally, AI - enabled devices can continuously learn from patient data, improving their performance over time and adapting to individual patient needs.

In conclusion, high - frequency electrotherapy provides a multi - faceted approach to the treatment of acute lumbar pain. With its rapid analgesic effect, ability to remodel muscle activation patterns, and synergistic effects on inflammation regulation and nerve repair, it is regarded as a promising therapeutic option. The necessity of an efficacy prediction model and equipment optimization further emphasizes the importance of personalized and safe treatment. Future research should focus on further exploring the fundamental mechanisms of high-frequency electrotherapy and developing more advanced equipment to enhance its clinical application.

5. Conclusion

This study aimed to evaluate the efficacy and mechanism of high-frequency pain therapy in acute lumbar pain. The results offer compelling evidence that high- frequency electrotherapy is a highly effective treatment modality for acute lumbar pain, operating through a triple-action mechanism.

First and foremost, the high-frequency electrotherapy has a remarkable analgesic effect. The non-thermal effect of the 100kHz current directly influences the cell membrane potential, inhibiting the opening of Nav1.7 sodium channels and TRPV1 channels. The significant down-regulation of TRPV1 expression (29.4% in the treatment group) and its positive correlation with the reduction in VAS scores confirm the central role of ion channel regulation in rapid pain relief. This mechanism interrupts the transmission of pain signals from the periphery to the central nervous system, providing prompt analgesia.

Secondly, the therapy effectively remodels muscle activation patterns. In acute lumbar pain, excessive activation of the erector spinae muscles is a pathological feature. The thermal effect of high-frequency electrotherapy promotes local blood circulation, reducing lactic acid accumulation, while the non-thermal effect inhibits the excitability of γ - motor neurons. This dual - action leads to a 37.8% reduction in the root mean square (RMS) of the erector spinae muscle at rest and an increase in the median frequency (MF) of the multifidus muscles, indicating improved muscle function and a reversal of central sensitization.

Thirdly, high-frequency electrotherapy shows significant anti - inflammatory and nerve-repair effects. The treatment group had a more substantial decline in IL-6 and TNF-α levels compared to the control group, attributable to the acceleration of inflammatory factor clearance through increased blood flow and the inhibition of the NF-κB pathway. Moreover, the 22.3% increase in BDNF level promotes the repair of dorsal root ganglion neurons and enhances the function of the descending inhibitory pathway, which can prevent the development of chronic low back pain.

The efficacy prediction model developed in this study is also of great clinical value. It reveals that patients with IL-6>25pg/ml and a disease course > 5 days respond poorly to high - frequency electrotherapy. This finding emphasizes the importance of personalized treatment, enabling clinicians to adjust treatment plans, such as early combined treatment with drugs or nerve block, to improve outcomes.

In terms of safety, although three cases of skin erythema occurred in the treatment group due to poor electrode contact, this points out the direction for equipment optimization. Improving the real time impedance feedback function and integrating AI algorithms into the equipment can ensure proper electrode contact, adjust power density automatically, and minimize the risk of adverse effects.

In conclusion, high-frequency electrotherapy is a safe and highly effective treatment for acute lumbar pain, with a clear mechanism of action and great potential for personalized application. Future research should focus on further exploring its underlying mechanisms and developing more advanced equipment to enhance its clinical application and benefit more patients.

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