Review

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Advances in Research and Prospective Applications of Molecular Hydrogen in Cancer Therapy

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Abstract: Molecular hydrogen, as an emerging therapeutic approach, has made significant progress in the field of cancer treatment over the past five years. Multiple in vitro and in vivo experiments have demonstrated that molecular hydrogen has antioxidant, anti-inflammatory, and regulatory impacts on cellular signaling pathways. It can selectively eliminate hydroxyl radicals and peroxynitrite anions, reducing oxidative stress damage to cells and possibly preventing the growth and spread of cancer cells. From a molecular mechanism viewpoint, molecular hydrogen influences the metabolism and survival conditions of cancer cells through regulating signaling pathways. In animal model studies, molecular hydrogen intervention enhanced the body's anti-tumor immune response and improved the tumor microenvironment. In terms of application prospects, molecular hydrogen therapy has shown the advantages of low toxicity and high biological safety, and can be combined with traditional cancer treatment methods such as chemotherapy and radiotherapy to reduce their side effects and potentially enhance treatment efficacy. However, cancer treatment with molecular hydrogen still encounters challenges, like the administration method, dosage control, and the specific action mechanisms of hydrogen in various types of cancer, which require further clarification.

Keywords: hydrogen; medicine; cancer

As one of the major challenges in the global public health field, cancer has a high incidence and mortality rate, seriously threatening human life and health[1,2]. Traditional cancer treatment methods mainly include surgery, chemotherapy, radiotherapy, immunotherapy, etc., but these traditional treatment methods all have certain limitations. In recent years, with the in-depth study of the pathogenesis of cancer, finding new and more effective treatment methods has become an urgent task.

In recent years, molecular hydrogen has emerged as a promising therapeutic approach in cancer treatment due to its unique biological mechanisms and broad application potential[3–5]. Exploring the mechanism of molecular hydrogen therapy for cancer not only helps provide new treatment options for cancer patients, but may also bring new hope for improving the overall effectiveness of cancer treatment.

1. Biological Characteristics of Molecular Hydrogen

1.1. Hydrogen Selective Antioxidant

Molecular hydrogen has unique selective antioxidant properties, which make it potentially valuable in various medical fields such as cancer treatment. Under normal physiological conditions, the redox reactions within cells are in a dynamic equilibrium. However, when the body is stimulated by various internal and external factors such as radiation, exposure to chemicals, chronic inflammation, etc., it can lead to the production of a large amount of reactive oxygen species (ROS)[6]. ROS includes superoxide anions (O2-), hydrogen peroxide (H2O2), hydroxyl radicals (•OH), etc.

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Among them, superoxide anions can damage ferritin; Hydroxyl radicals have extremely strong oxidizing properties and can cause serious damage to biomolecules such as DNA, proteins, lipids, etc. inside cells, leading to cellular carcinogenesis and other lesions[7,8].

The selective antioxidant effect of hydrogen gas is primarily manifested in its capacity to specifically neutralize hydroxyl radicals and strong oxidizing substances like peroxynitrite anions (ONOO -). Meanwhile, its influence on physiologically functional reactive oxygen species such as superoxide anions and hydrogen peroxide is comparatively minor [9–11]. From a chemical perspective, hydrogen reacts with hydroxyl radicals to form water, a rapid and efficient process that mitigates cellular damage caused by free radicals. This selective action ensures that oxidative stress is counteracted without disrupting normal redox signaling, thereby maintaining cellular homeostasis. For example, in vitro studies on neonatal rat brain cells demonstrated that hydrogen-rich water treatment alleviated oxidative stress induced by hypoxia-ischemia via the Nrf2-HO-1 pathway, inhibited cell death, improved cerebrovascular function, and reduced brain damage without adverse effects on liver or kidney function [12].

The damage induced by ionizing radiation results from the radioactive decomposition of hydroxyl radicals in H_2O. Studies have found that hydrogen can reduce hydroxyl radicals in the Fenton reaction, and cells treated with hydrogen can significantly inhibit radiation-induced apoptosis and increase the viability of human intestinal epithelial cells[13]. Also, experimental evidence shows that hydrogen molecules have a protective effect on radiation-induced heart damage[14]. This indicates that hydrogen, through its selective antioxidant effect, to some extent protect cells from oxidative damage caused by radiation, and has the potential to serve as a radiation protective agent, providing a theoretical basis for its potential application in adjuvant therapy during cancer radiotherapy.

Numerous experimental studies have shown that molecular hydrogen can selectively clear highly toxic ROS and inhibit multiple ROS-dependent signaling pathways in cancer cells, which thereby suppresses cancer cell proliferation and metastasis[15–17]. These research results suggest that the antioxidant effect of molecular hydrogen may be one of the important mechanisms for its anti-cancer effect.

1.2. Research on the Anti-Inflammatory Mechanism of Hydrogen Gas

Inflammation plays an important role in the occurrence, development, and metastasis of cancer. The inflammatory environment not only promotes the proliferation and survival of cancer cells, but also provides a favorable microenvironment for invasion and metastasis[18,19]. Hydrogen has significant anti-inflammatory mechanisms, mainly achieved through the following pathways.

Hydrogen can inhibit the activation of inflammation-related signaling pathways. Multiple animal experiments on lipopolysaccharide-induced diseases have found that inhaling high concentrations of hydrogen can prevent acute lung injury by inhibiting NF - κB and catalase mediated inflammation and oxidative stress in a sirt1-dependent manner[20], or by activating Nrf2 and then inhibiting the NF - κB signaling pathway to promote its anti-inflammatory and anti-apoptotic effects and improve lung injury[21]. Experimental studies demonstrate that oral administration of hydrogen-rich water ameliorates chronic intestinal inflammation in rat models. This protective effect is achieved through Nrf2 pathway activation, which counteracts NF-κB-mediated pro-inflammatory signaling [22]. In the study of hydrogen treatment for vascular dementia rats, it was observed that hydrogen can improve neurological damage and cognitive dysfunction in vascular dementia rats by inhibiting ROS/NLRP3/IL-1β - related oxidative stress and inflammation[23]. Hiroshi Matsuura et al. revealed through experiments that hydrogen can weaken inflammatory pathway signaling by inhibiting potential upstream regulatory factors, thereby improving the survival rate of septic mice [24].

Hydrogen exerts immunomodulatory effects by regulating the functional polarization of immune cells. Under inflammatory conditions, macrophages demonstrate distinct phenotypic and functional dichotomies: M1-type macrophages predominantly mediate pro-inflammatory responses

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and exert antitumor activity, whereas M2-type macrophages are characterized by anti-inflammatory properties, tissue remodeling capacity, and pro-angiogenic functions [25–27]. Notably, tumor-associated macrophages (TAMs) play a pivotal role in early carcinogenesis by establishing a supportive niche for cancer stem cell survival and proliferation [28].

Emerging evidence demonstrates that hydrogen therapy modulates macrophage plasticity through NF-κB signaling pathway inhibition. Experimental studies reveal that molecular hydrogen promotes phenotypic transition from pro-inflammatory M1 to anti-inflammatory M2 macrophages, effectively mitigating radiation-induced pulmonary inflammation [29]. Furthermore, in chronic obstructive pulmonary disease (COPD) models, hydrogen administration attenuates alveolar inflammation through dual mechanisms: suppression of M1 polarization and potentiation of M2 activation in alveolar macrophages [30].

Additionally, the direct clearance effect of hydrogen on inflammatory cytokines serves as a crucial mechanism. Experimental studies demonstrate that hydrogen chemically interacts with inflammatory factors, leading to their structural deactivation. This interaction effectively suppresses systemic expression of inflammatory mediators, thereby minimizing inflammation-induced physiological damage [31,32].

1.3. Regulatory Functions of Hydrogen Signaling

Experimental evidence indicates that hydrogen modulates the mitogen-activated protein kinase (MAPK) signaling pathway through regulation of key protein phosphorylation states. Specifically, hydrogen suppresses p38 MAPK activation by inhibiting its phosphorylation, consequently normalizing signaling activity to ameliorate inflammation and cellular apoptosis in preeclampsia models [33]. Further investigations demonstrate hydrogen's therapeutic potential in Staphylococcus aureus-induced murine mastitis. Hydrogen administration attenuates pathological progression via dual inhibition of TLR2 and Nod2 signaling pathways, leading to reduced phosphorylation levels in both MAPK and NF-κB cascades [34]. Notably, mechanistic studies by Zhang et al. reveal concentration-dependent antitumor effects of hydrogen in colorectal cancer. High-concentration hydrogen therapy suppresses malignant cell proliferation through pAKT/CD1 pathway inhibition, highlighting its targeted regulatory capacity in oncogenic signaling [35].

Hydrogen demonstrates regulatory effects on the phosphatidylinositol 3-kinase (PI3K)/protein kinase B (Akt) signaling pathway. Experimental studies using lung cancer cell models reveal that hydrogen treatment significantly reduces phosphorylation of Akt in the PI3K/Akt axis while elevating superoxide dismutase activity [36]. These molecular alterations disrupt cellular metabolic processes and anti-apoptotic mechanisms, ultimately suppressing proliferation and enhancing apoptosis in non-small cell lung cancer cells. Such findings highlight hydrogen's capacity to modulate critical signaling pathways, offering novel therapeutic strategies for lung cancer intervention.

Furthermore, hydrogen modulates transcriptional regulation by targeting nuclear factor erythroid 2-related factor 2 (Nrf2). Mechanistically, hydrogen promotes Nrf2 binding to antioxidant response elements (ARE), orchestrating differential regulation of redox-related genes. This molecular intervention enhances cellular antioxidant defenses via upregulation of superoxide dismutase (SOD), glutathione peroxidase (GPx), and catalase (CAT), while suppressing pro-oxidant enzymes such as myeloperoxidase. Collectively, these effects mitigate oxidative damage and reduce apoptosis, underscoring hydrogen's dual regulatory role in cellular redox homeostasis [37,38].

1.4. The Protective Effect of Hydrogen on Mitochondria

It has been demonstrated that molecular hydrogen is capable of safeguarding mitochondria against oxidative stress damage, sustaining energy production, and facilitating the correction of hypoxic conditions[21][39]. In certain experiments, researchers have noted that molecular hydrogen can notably enhance mitochondrial function and boost cellular energy metabolism levels[40,41]. This

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protective effect not only aids in enhancing the overall health of patients but also establishes a basis for enhancing the clinical effectiveness of cancer treatment.

2. The Impact of Hydrogen on Tumors

2.1. Inhibit Tumor Cell Proliferation

Hydrogen has shown significant effects on inhibiting tumor cell proliferation, and numerous studies have provided strong evidence for this. For example, in related studies on lung cancer cells, it was found that when lung cancer cells were exposed to a hydrogen environment, the expression of Ki67, a key indicator of cell proliferation, was significantly reduced[42]. Ki67 is a nuclear antigen closely related to cell proliferation. Its expression level directly reflects the proliferation activity. The reduction of Ki67 expression after hydrogen treatment clearly shows the inhibitory effect of hydrogen on the proliferation of lung cancer cells.

Similar findings have also been made in the field of liver cancer research. Experiments using in vitro and animal models have shown that the proliferation rate of liver tumor cells in mice treated with hydrogen is significantly slowed down[43]. This means that hydrogen can also effectively inhibit the proliferation of hepatocellular carcinoma cells in the in vivo environment.

In some in vitro cell culture experiments, for a variety of tumor cell lines, such as glioblastoma, colorectal cancer, gastric cancer, breast cancer and other cell lines, inhibition of cell proliferation was also observed after hydrogen was introduced[16][44–47]. These research results collectively indicate that hydrogen has a wide range of effects in inhibiting tumor cell proliferation, and this inhibitory effect is not limited to a specific type of tumor cell, but is manifested in multiple types of tumor cells.

2.2. Inducing Apoptosis of Tumor Cells

Hydrogen not only inhibits the proliferation of tumor cells, but also plays an important role in inducing tumor cell apoptosis. Apoptosis is an important way of programmed cell death, which is crucial for maintaining normal physiological functions and homeostasis in the body. During the occurrence and development of tumors, tumor cells often evade normal apoptosis mechanisms, allowing for unlimited proliferation. The intervention of hydrogen may reactivate the apoptosis program of tumor cells.

The relative proportional relationship between Bax and Bcl-2 is crucial in determining whether cells enter the apoptotic program. Taking human esophageal squamous cell carcinoma cells as an example, relevant studies have found that after hydrogen molecule treatment, the Bax/Bcl-2 ratio of human esophageal squamous cell carcinoma cells significantly increases, indicating that hydrogen can induce cell apoptosis[48].

In vitro and in vivo experimental studies have shown the following. The apoptosis rate of cervical cancer cells treated with hydrogen gas is significantly increased. Meanwhile, cell proliferation and oxidative stress levels are reduced[49]. Experiments on mice with human lung adenocarcinoma have shown that the protein expression levels of X-linked cell apoptosis inhibitor (XIAP) and baculovirus apoptosis protein repeat inhibitor 3 (BIRC3) in tumor tissues treated with hydrogen are significantly reduced compared to the control group[50]. This result indicates that hydrogen promotes the apoptosis of lung adenocarcinoma cells by decreasing the expression of XIAP and BIRC3 proteins.

Similar phenomena were observed in studies on hepatocellular carcinoma cells. In murine liver cancer models, hydrogen treatment significantly elevated Caspase-3 activity and increased apoptotic cell populations—as confirmed by apoptosis-related enzymatic assays and histopathological analysis of tumor tissues. The enhanced Caspase-3 activity indicates effective activation of programmed cell death pathways . The experimental data demonstrate that the synergistic effect of hydrogen and radiotherapy induces tumor cell death via dual mechanisms: ① direct DNA damage from ionizing radiation and ② programmed apoptosis mediated through AMPK signaling modulation, caspase-3 pathway activation, and apoptosis-inducing factor (AIF)-mediated genomic degradation[51].

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2.3. Interference with Tumor Metabolic Pathways

The interference of hydrogen with tumor metabolic pathways also reflects its impact on tumor cells. The metabolism of tumor cells is significantly different from that of normal cells, and tumor cells often have higher metabolic activity to meet their requirements for rapid proliferation and growth. Hydrogen disrupts tumor cell homeostasis through multi-target modulation of metabolic pathways, compromising their survival and proliferative capacity.

Aerobic glycolysis is an important energy-obtaining way for tumor cells in terms of their energy metabolism. Even under aerobic conditions, tumor cells preferentially choose the glycolysis pathway to produce energy, a phenomenon termed as the "Warburg effect"[52]. Research has discovered that hydrogen can directly inhibit glycolytic enzymes' activity and reverse the energy metabolism pathways' switch[53]. Hydrogen might influence the normal metabolism and proliferation of tumor cells by lowering the energy acquisition efficiency via glycolysis pathways.

Beyond energy metabolism, hydrogen exerts regulatory effects on tumor lipid homeostasis. Mechanistic studies reveal its ability to inhibit fatty acid peroxidation in neuroblastoma models while modifying lipid composition to disrupt energy-yielding processes [54]. These dual interventions in lipid synthesis and catabolism collectively constrain neoplastic growth.

Hydrogen exerts multiple effects on the growth and development of tumor cells from various perspectives, such as inhibiting cell proliferation, inducing apoptosis, and interfering with metabolic pathways, offering a potential effective approach for cancer treatment.

3. Exploration of Molecular Hydrogen Drug Delivery Technology

The common hydrogen intervention methods currently encompass hydrogen inhalation, hydrogen water drinking, intraperitoneal injection of hydrogen-rich water, hydrogen bath, etc.

Inhaling hydrogen gas is a prevalent intervention approach. For instance, placing experimental animals in a specially designed gas inhalation apparatus and enabling them to breathe a mixed gas containing a certain concentration of hydrogen gas. In some studies, the hydrogen concentration can exceed 60%, and it is mixed with other gases like oxygen in a certain proportion to ensure that animals can breathe normally while consuming an adequate amount of hydrogen[55]. By adjusting parameters such as gas flow rate and inhalation time to control the intake of hydrogen gas, the effects of different inhalation durations and concentrations on tumor development were observed[56,57].

Rich hydrogen water pertains to water that contains a high concentration of dissolved hydrogen gas. In the experiment, animals will be provided with specially prepared hydrogen-rich water for free consumption. There are diverse methods for preparing hydrogen-rich water, encompassing dissolving a considerable amount of hydrogen gas in water via electrolysis and other techniques, dissolving hydrogen tablets, and injecting hydrogen gas into drinking water or physiological saline[58,59]. Provide animals with hydrogen-rich water and continuously observe its effects on cancer-related indicators, such as tumor marker levels and changes in tumor volume[60,61].

Intraperitoneal injection of a hydrogen-rich solution involves directly injecting a solution with a high hydrogen gas concentration into the animal's abdominal cavity. Preparing hydrogen-rich solutions typically demands special equipment and procedures to ensure the stable dissolution of hydrogen in the solution and the maintenance of a specific concentration[62]. The injection dosage and frequency will be precisely determined based on the animal type, body weight, and experimental purpose. For example, for rats, a hydrogen-rich solution may be injected every other day, with each injection volume calculated according to a certain proportion of body weight, usually around 5 milliliters per kilogram of body weight[63]. In this way, hydrogen can enter the animal's circulatory system more directly and quickly act on tumor tissues and their microenvironment.

A hydrogen bath is an intervention approach that entails absorbing hydrogen gas via the skin. When the skin is immersed in water containing hydrogen gas, hydrogen gas can enter the body through the skin. Hydrogen can promote the metabolism of skin cells, increase the moisture content

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of the skin, improve the elasticity and luster of the skin, and thus have a certain preventive and therapeutic effect on skin diseases and skin aging[64].

Regarding skin beauty, hydrogen baths can enhance the skin's appearance and reduce skin aging phenomena like wrinkles and pigmentation[65]. For patients with chronic inflammatory skin diseases, hydrogen baths can alleviate symptoms such as skin itching, erythema, and papules, and improve their quality of life[66]. In clinical practice, it has also been observed that storing organs in hydrogen-rich water baths can significantly reduce myocardial injury and inflammatory events. Transplants stored in hydrogen-rich water baths also exhibit less mitochondrial damage and higher adenosine triphosphate content[67].

Different hydrogen intervention methods complement each other in animal experiments, providing diverse data and observation perspectives for studying the effectiveness of molecular hydrogen therapy for cancer from different perspectives.

4. Molecular Hydrogen Combined with Other Therapies

4.1. Research Progress on Combined Radiotherapy

Radiotherapy remains a mainstay therapeutic modality in oncology, though it invariably inflicts collateral damage on healthy tissues during tumor eradication. Recent scientific investigations have increasingly focused on combining molecular hydrogen with radiation regimens, seeking to determine whether their synergistic interaction can enhance therapeutic outcomes while minimizing adverse effects associated with radiation therapy.

Multiple experiments on the combined application of molecular hydrogen and radiotherapy have provided strong evidence. For example, in radiation therapy studies for liver cancer, patients with liver cancer were randomly divided into a hydrogen-rich water group and a placebo water group. Most radiation-induced side effects, including fatigue, nausea, diarrhea, dry mouth, loss of appetite, hair loss, skin pain, and depression, are often linked to increased oxidative stress and inflammation. From the first day of radiotherapy, patients drank hydrogen-rich water or placebo water for 6 weeks. It was shown that patients who drank hydrogen-rich water had a significant reduction in loss of appetite and taste disorders, thereby improving their quality of life. During radiotherapy, patients who drank placebo water exhibited a significant deterioration in endogenous serum antioxidant activity. In contrast, those who drank hydrogen-rich water maintained their biological antioxidant activity even after 6 weeks of radiotherapy, without influencing the anti-tumor effect of radiotherapy[68]. In radiation therapy experiments on multiple tumor models in mice and rabbits, it was found that hydrogen intervention improved tumor response by increasing cell apoptosis, inducing DNA damage, and enhancing radiation sensitivity[43].

Mechanistically, radiotherapy induces substantial reactive oxygen species (ROS) generation that not only inflicts collateral cellular damage but potentially drives tumor adaptive responses through oxidative stress signaling, ultimately diminishing therapeutic efficacy[69]. Molecular hydrogen exerts selective antioxidant effects through preferential neutralization of cytotoxic hydroxyl radicals while preserving physiologically essential oxidants. When administered concurrently with radiation, hydrogen therapy demonstrates multimodal radioprotective capacities: attenuating radiation-induced double-strand DNA breaks and mitochondrial membrane potential collapse in epidermal keratinocytes; suppressing inflammatory cytokine cascades; preventing histopathological manifestations including follicular damage, dermal hyperplasia, and leukocyte infiltration; and modulating apoptotic regulators via decreased Bax/Bcl-2 ratios and caspase activation, collectively mitigating radiation dermatitis severity[70].

Nevertheless, current clinical investigations remain constrained by limited cohort sizes, necessitating expanded multicenter trials with longitudinal monitoring to comprehensively establish the safety profile and therapeutic optimization parameters for hydrogen-radiotherapy combinations.

4.2. Observation of the Effect of Combined Chemotherapy

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As a cornerstone of oncological intervention, chemotherapy employs cytotoxic agents to impede neoplastic proliferation, yet invariably induces multisystemic toxicity—including but not limited to myelosuppression, hepatorenal toxicity, and gastrointestinal complications—via non-specific cytotoxicity[71–73]. This therapeutic paradox necessitates exploration of combinatorial strategies to potentiate antitumor efficacy while attenuating iatrogenic harm, with hydrogen coadministration emerging as a promising investigational paradigm.

Accumulating preclinical and clinical evidence substantiates hydrogen's chemosensitizing potential. In a 4-week inhalation trial involving chemotherapy-intolerant patients, hydrogen therapy demonstrated multidimensional benefits: significant alleviation of cancer-related fatigue, insomnia, anorexia, and pain syndromes; marked reduction in serum tumor biomarkers; and clinically meaningful improvement in quality-of-life indices[74]. A clinical trial study on advanced non-small cell lung cancer found that the tumor progression of patients in the hydrogen-combined chemotherapy group was controlled, and adverse drug events in these patients gradually decreased or even disappeared[57]. Regarding its mechanism of action, drinking hydrogen-rich water can change the diversity and structure of the gut microbiota in mice, and regulate the gut microbiota to alleviate the pathological neuropathic pain caused by chemotherapy drugs[60].

These findings elucidate the synergistic therapeutic profile of molecular hydrogen co-administered with chemotherapy, demonstrating concurrent enhancement of tumor response rates and significant attenuation of chemotherapy-induced toxicity. However, it should also be pointed out that current research on the combined application of molecular hydrogen and chemotherapy is mostly in the preclinical or small-scale clinical trial stage, and more large-scale, multi-center clinical trials are needed to further verify its effectiveness and safety, providing a more sufficient basis for clinical application.

4.3. Immunotherapeutic Synergy

The emergence of tumor immunotherapy has demonstrated significant therapeutic potential in oncology. However, this therapeutic modality faces dual challenges of heterogeneous efficacy across patient populations and immune-related adverse events (irAEs) in certain individuals[75]. Consequently, investigations into the synergistic interplay between molecular hydrogen and immunotherapy have gained substantial momentum, seeking to amplify therapeutic responses while minimizing treatment-associated toxicities.

Immunotherapy primarily functions through activation of endogenous immune defenses, particularly via enhancement of T-cell-mediated tumor recognition and cytotoxicity. Counterintuitively, tumor cells employ multifaceted immune evasion mechanisms during this process. Preclinical evidence reveals that hydrogen therapy potentiates tumor-specific immune activation, marked by elevated CD4+ and CD8+ T-cell infiltration within tumor tissues, while circumventing PD-L1 upregulation. This dual mechanism not only augments immunotherapeutic efficacy but also reduces immune escape phenomena, thereby proposing a novel combinatorial therapeutic paradigm[76].

The bilateral tumor transplantation models of "cold tumor" (4T1 cells) and "hot tumor" (MC38 cells) have demonstrated that hydrogen therapy can not only directly eliminate tumor cells but also suppress tumor-promoting and immunosuppressive factors in cancer-related fibroblasts, thereby enhancing the immune activity of CD4+T cells and offering a systematic anti-tumor immune stimulation strategy by remodeling the tumor matrix microenvironment[77].

The electrocatalytic hydrogen therapy experiment suggests the following. Electrocatalytic hydrogen therapy can induce mitochondrial dysfunction and oxidative stress. It can activate cell pyroptosis through the typical ROS/caspase-1/GSDMD signaling pathway. It can enhance CD8 T lymphocyte infiltration into tumors. And it can reverse the immunosuppressive microenvironment[78]. Collectively, these experimental findings validate the translational feasibility of hydrogen-immunotherapy combination regimens in oncology.

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5. Future Perspectives in Hydrogen Therapy

Significant progress has been made in the research of molecular hydrogen in cancer treatment. However, it is still in the preclinical and preliminary clinical research stage. Therefore, further thorough research is needed to fully confirm the effectiveness and safety of molecular hydrogen before its wide application in clinical practice. Precisely analyzing the specific targets and signaling pathways of molecular hydrogen is one of the key directions to be addressed in the future.

At present, it is known that molecular hydrogen has various biological effects, such as antioxidant and anti-inflammatory. It can also affect the proliferation, apoptosis, and other behaviors of tumor cells to some extent. However, the exact molecular targets of its role in cells are not fully understood.

The complex interaction between molecular hydrogen and the tumor microenvironment requires further research. The tumor microenvironment is crucial for the occurrence, development, metastasis, and response to treatment of tumors. Can molecular hydrogen regulate the functional status of various cells in the tumor microenvironment, such as immune cells, fibroblasts, and endothelial cells? This could change the ecology of the entire tumor microenvironment and achieve the goal of inhibiting tumor growth.

The therapeutic effects of molecular hydrogen in different cancers and individuals, and the formulation of personalized treatment plans, are key issues to be addressed in the future. Cancer is a highly heterogeneous disease. Different cancer types show significant differences in etiology, pathological characteristics, and molecular biological mechanisms. Current research has found that molecular hydrogen has therapeutic potential in multiple cancers, but its specific effects and mechanisms may vary among different cancer types. Therefore, developing personalized molecular hydrogen therapy plans based on the specific condition, individual characteristics, and other factors of cancer patients to attain the best treatment effect is an important scientific issue that must be solved in future clinical applications.

In addition, the optimal administration method, dosage, and treatment duration of molecular hydrogen therapy for cancer also need to be further refined and established. It is also crucial to emphasize the combination of molecular hydrogen therapy with other treatment modalities to explore more effective comprehensive treatment plans.

6. Conclusion

Hydrogen therapy, an emerging approach in cancer treatment, possesses unique biological traits and multiple potential mechanisms of functioning. Current research shows that hydrogen therapy has certain effects in treating various types of cancer, such as reducing the side effects of conventional treatments, and inhibiting tumor cell growth and metastasis. However, hydrogen therapy still encounters numerous challenges in cancer treatment, like an unclear mode of action, a lack of standardization in evaluating treatment efficacy, and the need for further research on safety and long-term effects. In the future, it is essential to further advance the development of hydrogen therapy in cancer treatment. This can be achieved by conducting in-depth studies on its mechanism of action, carrying out large-scale clinical trials, and exploring combination therapies to offer new treatment choices for cancer patients.

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