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Clinical Application and Prospect of New Radiotherapy Technology in Cancer Treatment

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Abstract: *Objective:* Carbon ion therapy, a new radiotherapy technology, has shown its remarkable efficacy and potential in cancer treatment, especially in the treatment of refractory tumors. *Methods:* This paper clarifies the physical basis, technological change, and clinical practice effect of carbon ion therapy, comprehensively discusses the future prospects, and evaluates the clinical application effect. *Results:* The technology has significantly improved the treatment effectiveness and received a positive response from patients. *Conclusion:* Carbon ion therapy technology has become a major innovation in the field of cancer treatment. It not only has a profound impact on many current cancer therapy methods but also indicates the application blueprint for a wider range of cancer types in the future, showing a new chapter of medical technology advancement.

Keywords: Carbon ion therapy; Radiation therapy; Cancer treatment; Clinical application; Therapeutic effect

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1. Introduction

Radiotherapy, as an important means of cancer treatment, has long developed in its technology and application. Carbon ion therapy uses heavy ion rays to accurately strike tumor cells, significantly improves the accuracy of treatment, and reduces the damage to surrounding normal tissues [1]. Compared with traditional radiotherapy, carbon ion therapy has significantly improved the efficiency of deep tumor control, especially in the treatment of tumor types that are not sensitive to traditional radiotherapy. A landmark leap in cutting-edge technology is to improve the effectiveness of treatment and the quality of survival.

2. Technical basis of carbon ion therapy

2.1. Physical principles

As one of the heavy ions, carbon ions show more significant linear energy transfer characteristics compared with X-ray and electron beams [2,3]. When charged particles like carbon ions penetrate matter, they start transferring kinetic energy to the medium, in contrast to photons. This process, known as linear energy transfer, intensifies as the particle decelerates and ceases once the kinetic energy is fully released. This results in a depth dose curve where a low dose is administered to the surface, but increases sharply and peaks at the particle's stopping point (**Figure 1**). This sharp peak is called the Bragg peak, characterized by energy being precisely deposited within a specific geometric range. The Bragg peak's distinctive feature, compared to photons and protons, illustrates the precise energy delivery advantage of carbon ion therapy.

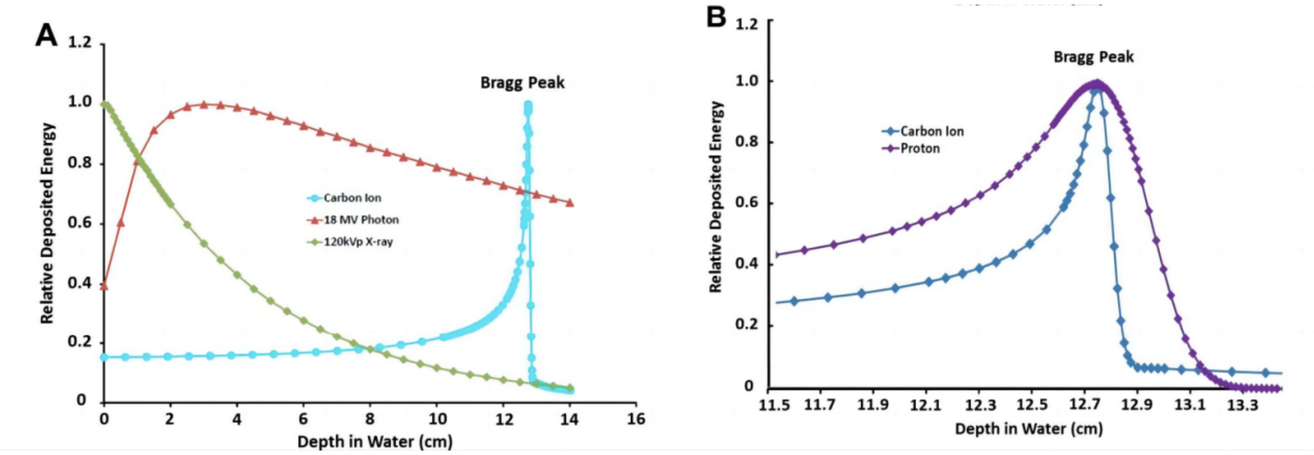

Figure 1. (A) Percentage depth dose (PDD) curves comparing carbon ion beams to high (18 MV) and low (120 kVp) energy photon beams. (B) Percentage depth dose curves comparing carbon ion to proton beams [2].

When carbon ion bundles penetrate tumor cells, they collide with cellular molecules, especially DNA molecules, resulting in direct or indirect breakage of DNA duplexes. Such damage prevents the cells from repair, leading to programmed death or loss of reproduction. Compared with traditional radiation therapy, carbon ion radiotherapy shows a significant advantage in the field of refractory tumors by virtue of its more complex damage mechanism to DNA and higher difficulty in repair.

2.2. Technological development

In the early 1970s, the Radioisotope Laboratory, University of California, Berkeley, carbon ion therapy technology achieved a leap forward. Initially, the therapy aims to explore the impact of ion beams on cell biology and then tap into its potential value in cancer treatment. Japan and Germany pioneered the clinical application of carbon ion therapy technology and established the first professional facilities in the 1990s.

With the continuous innovation of accelerator technology, carbon ions can be accelerated efficiently and stably, greatly improving the accuracy and safety standards of treatment. Today, the treatment planning system has been optimized to tailor the treatment strategies according to the patient's special circumstances, accurately control the carbon ion beam dose and its distribution, and minimize the impact on the surrounding normal tissue [4]. Driven by the combination of scientific and technological progress and accumulation of clinical experience, carbon ion therapy has transformed from experimental therapy to quasi-mature cancer treatment.

3. Clinical applications of carbon-ion therapy

3.1. Review of the clinical studies

Carbon ion therapy, since its pioneering application in Japan in 1994, highlights its unique value in the clinical field. Since then, extensive clinical research has been explored in various fields of cancer treatment, and the effectiveness and safety of the innovative application of this technology have been comprehensively reviewed and verified. Many studies have confirmed that carbon ion therapy for head and neck cancer, brain cancer, prostate cancer, and specific refractory soft tissue sarcoma, with significant local efficacy and patient survival advantages [5,6]. The latest clinical trials have shown that the five-year survival rate of refractory nasopharyngeal carcinoma patients treated with carbon ion therapy has increased significantly, significantly reducing the risk of recurrence compared with conventional radiation therapy.

3.2. Treatment indications

Carbon ion therapy techniques are designed to deal with cases of tumors that are difficult to remove surgically or that are insensitive to conventional radiotherapy. The technical iteration and the deepening effect have made the treatment methods widely used in all kinds of tumor prevention and treatment. Carbon ion therapy technology, with its unique advantages, is especially suitable for deep positioning, adjacent to key organ structures [7,8]. This technology ensures that the damage to the surrounding innocent and healthy tissues is minimized under the premise of high radiation dose output, reflecting the precise protection of the human physiological structure and the efficient combination of treatment. Carbon-ion therapy shows significant therapeutic advantages for deep tumors, such as pancreatic cancer and liver cancer, which are refractory to chemotherapy and conventional radiotherapy [9].

With its excellent physical and biological characteristics, carbon ion therapy has shown remarkable results in dealing with specific tumor therapy (**Figures 2** and **3**). These tumors usually include:

(1) Deep-seated tumors: For brain tumors and spinal cord tumors, carbon ion therapy can directly hit the tumor core, while carefully guarding the surrounding nerve structures to ensure safety [10].

(2) Radiologically refractory tumor: Through assessing the safety and efficacy of high-dose carbon ion radiation therapy in two fractions for hepatocellular carcinoma (HCC). It demonstrates promising local control and survival outcomes, highlighting the advantages of carbon ion therapy in treating liver cancer, which is typically resistant to conventional radiotherapy [11].

(3) Recurrent or difficult to surgically remove tumors: In the face of ineffective or inaccessible other therapies, carbon ion therapy offers a new non-invasive treatment option for patients [12]. This positions carbon ion therapy as a valuable alternative to surgical salvage and palliative chemotherapy in selected patients.

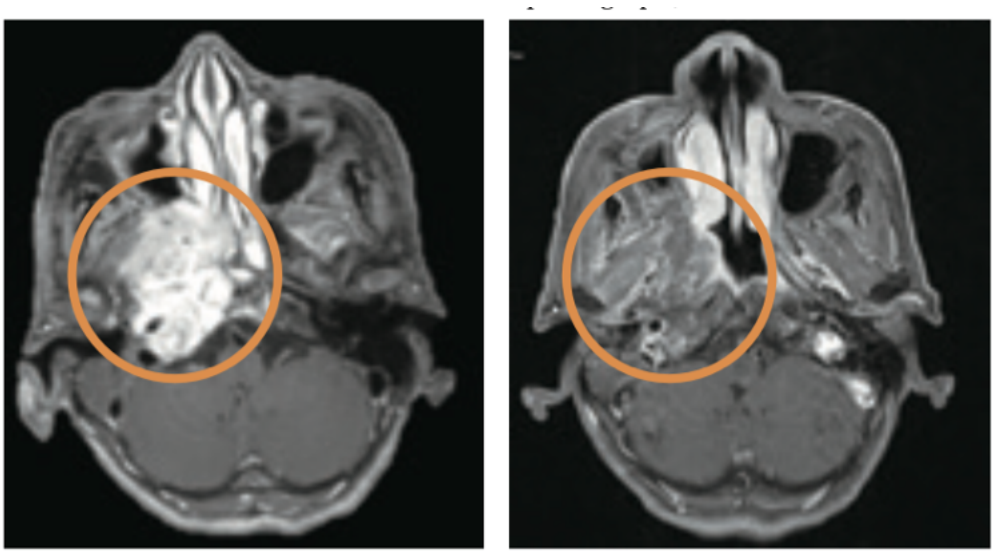

Figure 2. After 4 weeks of carbon ion treatment for head and neck cancer, compare the results using contrast-enhanced MRI after 6 months [13].

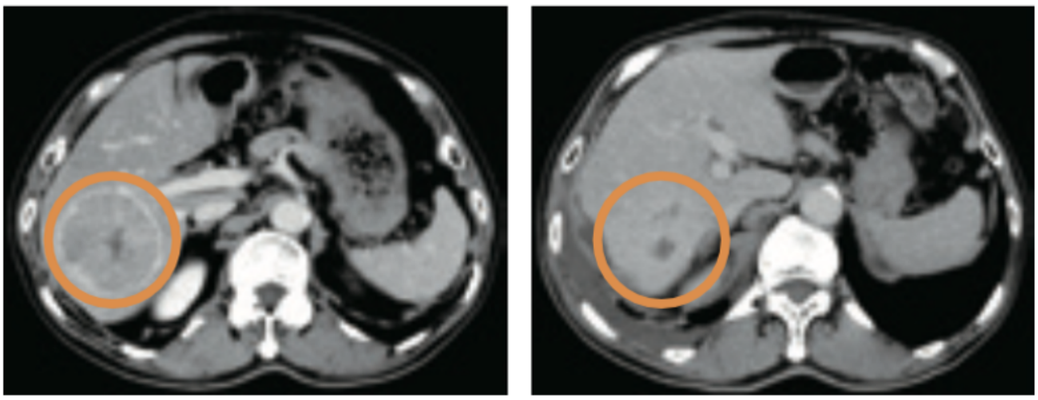

Figure 3. After 1 week of carbon ion treatment for hepatocellular carcinoma, compare the results using contrast-enhanced CT after 12 months [13].

3.3. Patient safety and response

Despite the significant advantages of carbon ion therapy, patient safety is always the primary consideration of treatment. To ensure the safety of patients receiving carbon ion therapy, all treatment centers are equipped with advanced monitoring and control systems to ensure precise control of radiation dose and prudent implementation of treatment procedures. The clinical team can conduct a comprehensive pre-treatment evaluation of patients, deeply analyze their health status and tumor characteristics, and tailor personalized treatment plans [14]. Detailed evaluation and model simulation are performed to ensure the safety and precision of carbon-ion therapy in complex clinical scenarios.

The management of patient response and side effects is the key link to ensure the success of the treatment. The clinical medical team ensures timely treatment optimization for various potentially inappropriate conditions by closely monitoring patient responses. During the whole process of treatment, patients will receive comprehensive health counseling and necessary support to fully understand the treatment procedures and their potential responses, and ensure the safety and comfort of the whole process of treatment.

4. Evaluation of the effect of carbon ion therapy

4.1. Efficacy comparison

Carbon ion therapy shows significant advantages over the field of radiation therapy, especially in dealing with those difficult or sensitive to location requirements. Compared with traditional X-ray and gamma-ray therapy, carbon ion therapy shows a more concentrated dose distribution advantage, which can accurately deliver a higher dose of radiation to tumor tissue and effectively reduce the damage to surrounding normal tissue [15].

Studies have shown that carbon ion therapy has significant advantages over traditional radiotherapy in the treatment of head and neck tumors, brain tumors, and some spinal tumors that are difficult to remove after surgery, which not only improves the survival chance of patients but also significantly improves their quality of life. Thanks to the high linear energy transfer characteristics of carbon ion therapy, its selective therapeutic effect is remarkable, which can greatly destroy tumor cells while maximizing the protection of normal cells.

4.2. Economic evaluation

In the short term, the direct cost of carbon ion therapy is higher than that of conventional radiotherapy. Over the long term, carbon ion therapy may be more effective in dealing with refractory tumors. The application of carbon ion therapy technology is expected to significantly reduce the long-term medical care needs of patients, while effectively decreasing the economic burden of subsequent treatment caused by tumor recurrence or metastasis [16].

The economic evaluation shows that although carbon ion treatment equipment is expensive and has a large initial investment, it has certain potential advantages in improving efficacy, shortening the treatment cycle, and reducing the recurrence rate. To evaluate the cost-benefit ratio of treatment, we can achieve the comprehensive effect of saving long-term medical expenses and improving the quality of life.

4.3. Analysis of patient quality of life

An important reason for the wide use of carbon ion therapy is its significant positive impact on patients' quality of life. Compared with traditional radiotherapy, carbon ion therapy relies on its precise dose distribution to minimize the damage to the surrounding healthy tissues, thus reducing the side effects during treatment and rehabilitation. Through assessing the risk of developing secondary primary cancers following carbon ion radiotherapy compared to photon radiotherapy and surgery. The results indicate that carbon ion radiotherapy is associated with a lower risk of secondary malignancies, emphasizing its safety and potential to maintain a higher quality of life compared to traditional therapies [17].

5. Future prospects and challenges

5.1. Technological innovation

In the future, technological innovation will become a key driving force in the field of carbon ion therapy, and improving the accuracy of treatment will become the top priority in research and development work. Equipment miniaturization is the key to the promotion of carbon ion therapy technology. At present, the scale of carbon ion therapy equipment is large and expensive, which hinders its popularity. The development of compact accelerators and beam transmission facilities can significantly reduce construction and operational costs and improve the availability of advanced therapeutic technologies [18].

It is necessary to introduce automation and machine learning algorithms to optimize treatment planning, shorten preparation time, and improve treatment efficiency. With the help of innovative means, carbon ion therapy has been a personalized and customized treatment plan for many patients.

5.2. Clinical application

Advancements in technology and therapeutic effectiveness are expected to deepen the use of carbon ion therapy across a broader range of cancer types, fostering innovative expansions in treatment. The research and exploration of the therapeutic potential of common tumors such as breast cancer and lung cancer and metastatic cancer have been launched, aiming to deepen the understanding of the treatment field of multiple tumors and enhance the research and development of innovative treatment programs. Carbon ion therapy, through the precise high-dose radiation concentration of target areas, injects new hope for cancer therapy that is difficult for conventional therapies. It is also being explored for non-cancerous deep neural system disorders, showcasing bold medical innovation and its potential to revolutionize healthcare by extending beyond traditional limitations.

5.3. Potential benefits of combination therapy

Combining carbon ion therapy with immunotherapy or targeted therapy represents an innovative approach to cancer treatment that leverages the unique benefits of these modalities to enhance therapeutic efficacy and patient outcomes [19,20]. These benefits include:

(1) Synergistic effects: Carbon ion therapy can induce complex DNA damage in cancer cells, leading to cell death and increased antigen presentation. This may make tumor cells more vulnerable to immune attack, enhancing the efficacy of immunotherapy. Additionally, targeted therapy can inhibit specific pathways that cancer cells use to survive and proliferate, potentially making them more susceptible to the destructive effects of carbon ion radiation.

(2) Reduced tumor resistance: Combining therapies can help in overcoming or preventing resistance to treatment. For instance, if a tumor starts to develop resistance to targeted therapy, the immunogenic cell death induced by carbon ion therapy could still promote an immune response against the tumor.

(3) Expanded indications: This combination could be particularly beneficial in treating tumors that are inherently resistant to conventional therapies or have relapsed after initial treatment. The precision of carbon ion therapy, combined with the systemic attack from immunotherapy, offers a robust approach to tackling difficult-to-treat cancers.

(4) Improved patient outcomes: Early research suggests that combining carbon ion therapy with immunotherapy or targeted therapy can lead to improved control of local and distant tumors, potentially leading to better overall survival rates and quality of life for patients.

6. Conclusion

Carbon ion therapy is significantly leading in many fields of cancer treatment, highlighting breakthrough advantages. It has become a general trend to deeply explore and optimize high-precision treatment technology to greatly improve the tumor efficacy and the quality of life of patients. Carbon ion therapy, as a new medical technology, has brought unprecedented hope to many patients with refractory tumors.

Disclosure statement

The author declares no conflict of interest.

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