ПРОТОННАЯ ТЕРАПИЯ: ФИЗИЧЕСКИЕ ОСНОВЫ И КЛИНИЧЕСКИЕ ПРИМЕНЕНИЯ

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Аннотация

В данной работе представлен комплексный анализ физических принципов, лежащих в основе протонной терапии, с акцентом на механизмы потери энергии и их клиническое значение. Взаимодействие протонов с веществом описывается с использованием уравнения Бете–Блоха, а явление пика Брэгга рассматривается как ключевой фактор, обеспечивающий точную локализацию дозы в радиотерапии. Дозиметрические характеристики и радиобиологические параметры, включая линейную передачу энергии (LET) и относительную биологическую эффективность (RBE), анализируются с точки зрения эффективности лечения. Результаты показывают, что протонная терапия обеспечивает более точное распределение дозы, снижение повреждения здоровых тканей и улучшение клинических исходов при лечении онкологических заболеваний.

Ключевые слова: протонная терапия, пик Брэгга, уравнение Бете–Блоха, LET, RBE, радиотерапия

PROTON THERAPY: PHYSICAL FOUNDATIONS AND CLINICAL APPLICATIONS

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Abstract

This paper presents a comprehensive analysis of the physical principles underlying proton therapy, focusing on energy loss mechanisms and their clinical implications. The interaction of protons with matter is described using the Bethe–Bloch equation, while the Bragg peak phenomenon is examined as the key factor enabling precise dose localization in radiotherapy. Dosimetric characteristics and radiobiological parameters, including Linear Energy Transfer (LET) and Relative Biological Effectiveness (RBE), are discussed in the context of treatment efficiency. The results demonstrate that proton therapy provides superior dose distribution, reduced damage to healthy tissues, and improved clinical outcomes in cancer treatment.

Keywords: proton therapy, Bragg peak, Bethe–Bloch equation, LET, RBE, radiotherapy

Introduction

Radiotherapy remains one of the primary modalities for cancer treatment, and its effectiveness strongly depends on how radiation energy is deposited within biological tissues. In conventional photon-based therapy, such as X-rays or gamma radiation, energy is gradually absorbed along the entire beam path, resulting in significant exposure of healthy tissues. In contrast, proton therapy represents an advanced form of particle therapy that utilizes charged particles with unique energy deposition characteristics. Protons release the majority of their energy at a specific depth within tissue, corresponding to the tumor location. This phenomenon, known as the Bragg peak, enables highly localized dose delivery and minimizes radiation exposure to surrounding healthy structures.

The aim of this study is to analyze the physical foundations of proton therapy and evaluate its clinical effectiveness from both dosimetric and radiobiological perspectives.

Materials and Methods

The interaction of protons with matter is primarily governed by Coulomb interactions with atomic electrons. As protons traverse a medium, they lose energy through ionization and excitation processes. The rate of energy loss is described by the Bethe–Bloch equation:

$$\frac{-dE}{dx}=\frac{4\pi z^2 e^4}{m_e v^2} n \ln\left(\frac{2 m_e v^2}{I}\right)$$

where

$\frac{dE}{dx}$is the stopping power,

$v$is the proton velocity,

I is the mean excitation potential of the medium.

This relationship indicates that as the proton slows down, the energy loss per unit path length increases significantly. Consequently, protons deposit a maximum amount of energy near the end of their range, forming the Bragg peak.

From a dosimetric perspective, the Linear Energy Transfer (LET) is defined as:

$$LET = \frac{dE}{dx}$$

LET describes the energy deposited per unit length and plays a crucial role in determining the biological effectiveness of radiation.

Another important parameter is the Relative Biological Effectiveness (RBE):

$$RBE = \frac{D_{reference}}{D_{proton}}$$

For proton therapy, RBE is typically around 1.1, indicating a slightly higher biological effectiveness compared to conventional photon radiation.

Results

Theoretical and experimental studies confirm that proton beams exhibit a distinct depth-dose distribution characterized by low entrance dose, a sharp maximum (Bragg peak), and negligible exit dose.

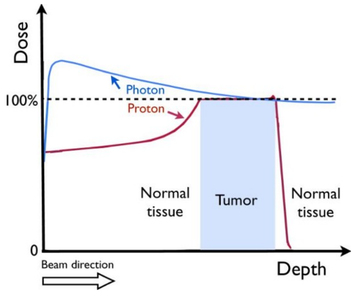

Figure 1. Depth–dose comparison of photon and proton beams. Photons deposit energy along the entire path, while protons deliver a peak dose at the tumor (Bragg peak) with minimal exit dose, sparing normal tissues.

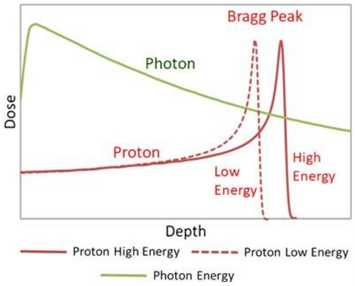

Figure 2. Depth–dose curves for photon and proton beams. Photons decrease gradually, while protons show a Bragg peak; higher energy protons reach deeper than lower energy ones.

This distribution leads to several clinically significant outcomes. First, the radiation dose delivered to healthy tissues is substantially reduced compared to photon therapy. Second, the tumor receives a highly concentrated dose, improving treatment precision. Clinical data indicate that proton therapy is particularly effective in treating tumors located near critical structures, such as the brain, spinal cord, and eyes. It is also widely used in pediatric oncology, where minimizing radiation exposure is essential for preventing longterm side effects. Dosimetric analyses further demonstrate that the exit dose in proton therapy is nearly zero, which significantly enhances its safety profile.

Discussion

The primary advantage of proton therapy lies in its ability to localize energy deposition within a well-defined region. This characteristic allows for highly conformal treatment of tumors while preserving surrounding healthy tissues. From a radiobiological standpoint, the moderate LET of protons results in controlled and predictable biological damage, primarily through DNA strand breaks. This makes proton therapy both effective and manageable in clinical settings.

However, several limitations must be considered. The infrastructure required for proton therapy, including cyclotrons and synchrotrons, is expensive and technologically complex. As a result, access to this treatment modality is limited. Additionally, uncertainties related to patient motion and tissue heterogeneity can affect dose accuracy. Advanced techniques such as pencil beam scanning and adaptive radiotherapy are being developed to address these challenges.

Conclusion

Proton therapy represents a significant advancement in modern radiotherapy, combining principles of nuclear and particle physics with clinical oncology. Its unique physical properties, particularly the Bragg peak, enable precise dose delivery and improved treatment outcomes.

By minimizing radiation exposure to healthy tissues, proton therapy offers substantial benefits, especially in complex and sensitive anatomical regions. Future developments in technology and cost reduction are expected to expand its accessibility and clinical applications.

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