БЫСТРАЯ НЕЙТРОННАЯ ТЕРАПИЯ: ФИЗИЧЕСКИЕ МЕХАНИЗМЫ, ДОЗИМЕТРИЯ И КЛИНИЧЕСКАЯ ЭФФЕКТИВНОСТЬ

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Аннотация

Быстрая нейтронная терапия представляет собой метод радиационного лечения с высоким линейным переносом энергии (LET), основанный на ядерных взаимодействиях, а не на электромагнитных процессах. В данной работе представлен детальный анализ взаимодействия нейтронов с биологическими тканями с акцентом на образование отдачных протонов, плотные ионизационные треки и усиленное биологическое повреждение. Дозиметрические характеристики, включая LET и относительную биологическую эффективность (RBE), рассмотрены в сравнении с фотонной и протонной терапией. Результаты показывают, что нейтронная терапия особенно эффективна при лечении радиорезистентных и гипоксических опухолей благодаря меньшей зависимости от кислорода и высокой сложности повреждений ДНК. Однако остаются существенные ограничения, связанные с распределением дозы и повреждением здоровых тканей.

Ключевые слова: быстрая нейтронная терапия, излучение с высоким LET, ядерные взаимодействия, отдачный протон, радиобиология, RBE, дозиметрия

FAST NEUTRON THERAPY: ADVANCED PHYSICAL MECHANISMS, DOSIMETRY AND CLINICAL EFFECTIVENESS

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Abstract

Fast neutron therapy represents a high-LET radiation modality that relies on nuclear interactions rather than electromagnetic processes. This study provides a detailed analysis of neutron interactions with biological matter, emphasizing recoil proton generation, dense ionization tracks, and enhanced biological damage. Dosimetric characteristics, including LET and Relative Biological Effectiveness (RBE), are evaluated in comparison with photon and proton therapies. The findings demonstrate that neutron therapy is particularly effective for radioresistant and hypoxic tumors due to its reduced dependence on oxygen

and increased DNA damage complexity. However, limitations related to dose distribution and normal tissue toxicity remain critical challenges.

Keywords: fast neutron therapy, high LET radiation, nuclear interaction, recoil proton, radiobiology, RBE, dosimetry

Introduction

Modern radiotherapy is fundamentally based on the controlled deposition of ionizing radiation energy within biological tissues. Conventional photon-based therapies operate through low-LET interactions, resulting in sparse ionization patterns and indirect DNA damage. While effective for many tumor types, these modalities are limited in treating hypoxic or radioresistant tumors. Fast neutron therapy introduces a fundamentally different interaction mechanism. As electrically neutral particles, neutrons do not interact via Coulomb forces but instead undergo nuclear interactions with atomic nuclei. These interactions generate secondary charged particles that produce dense ionization tracks, leading to complex and often irreparable biological damage. The significance of neutron therapy lies in its ability to overcome limitations of conventional radiotherapy. This paper aims to provide a comprehensive analysis of its physical principles, dosimetric behavior, and clinical applications within modern medical physics.

Theoretical Background and Methods

Neutron Interaction Mechanisms

Neutrons interact with matter primarily through:

- elastic scattering
- inelastic scattering
- nuclear reactions

The most important mechanism in biological tissue is elastic scattering with hydrogen nuclei, producing recoil protons.

$$E_p = \frac{4\, m_n m_p}{\left(m_n + m_p\right)^2} E_n$$

This equation shows that a significant fraction of neutron energy is transferred to protons, which then act as high-LET particles.

Energy Deposition and LET

Unlike photons, neutron-induced secondary particles deposit energy densely:

$$LET = \frac{dE}{dx} \approx 50 - 100 \ \ keV/\mu m$$

This high LET results in:

- clustered ionization
- multiple DNA double-strand breaks

- reduced repair probability

Radiobiological Effectiveness

The biological efficiency is quantified using:

$$RBE = \frac{D_{photon}}{D_{neutron}} \approx 2-5$$

Additionally, neutron therapy shows weak dependence on oxygen:

$$OE\,R_{neutron} \approx 1.5$$

compared to photons ($OER \approx 2.5-3$), making it highly effective for hypoxic tumors.

Results

Experimental and clinical studies indicate that neutron beams produce a relatively uniform depth-dose distribution without a pronounced Bragg peak. However, their biological effectiveness compensates for the lack of physical dose localization.

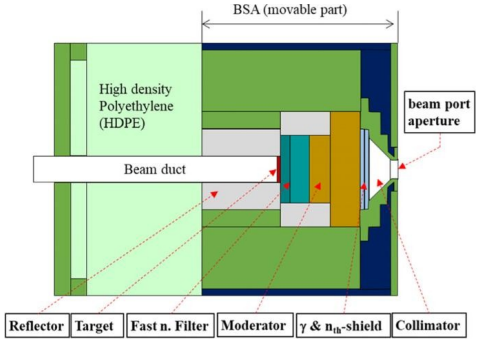

Figure. Schematic diagram of a neutron therapy beam system showing neutron production, moderation, filtering, and collimation before reaching the patient.

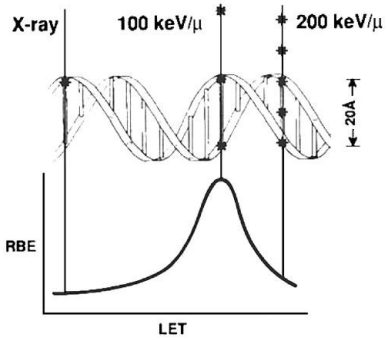

Figure. Relationship between LET and RBE: increasing LET leads to denser ionization and higher biological effectiveness.

Key observed outcomes include:

- increased tumor control probability (TCP)
- reduced dependence on oxygenation
- effectiveness in slow-growing tumors

Clinical success has been reported in:

- salivary gland tumors
- head and neck cancers
- prostate tumors

Discussion

The superiority of neutron therapy is fundamentally linked to its high LET. Dense ionization leads to complex DNA damage, including clustered lesions that are difficult for cellular repair mechanisms to resolve.

From a radiobiological perspective, neutron radiation induces:

- direct DNA strand breaks

- chromosomal aberrations
- apoptosis and necrosis

However, these advantages come with significant drawbacks. The lack of a Bragg peak means that neutron beams cannot achieve the same spatial precision as proton therapy. Consequently, surrounding healthy tissues are exposed to higher doses. Moreover, neutron sources require nuclear reactors or particle accelerators, making the technology expensive and less accessible. Dose calculation and treatment planning are also more complex due to mixed radiation fields and variable RBE.

Conclusion

Fast neutron therapy represents a unique and powerful approach in radiation oncology, combining nuclear physics principles with clinical applications. Its high LET and strong biological effectiveness make it particularly suitable for treating radioresistant and hypoxic tumors. Despite its limitations, including reduced dose localization and higher toxicity risk, neutron therapy remains an important modality in specialized clinical settings. Future developments in beam control, hybrid therapies, and radiobiological modeling are expected to further enhance its therapeutic potential.

References

1. Dzhumanov S., Sheraliyev M.U. *The validity of the BCS-like theory of Fermi-liquid superconductivity in overdoped cuprates* // International Journal of Modern Physics B. – 2024. DOI: 10.1142/S0217979224501406

2. Hall E. J., Giaccia A. J. *Radiobiology for the Radiologist*. – 8th ed. – Philadelphia: Wolters Kluwer, 2019.

3. Joiner M., van der Kogel A. *Basic Clinical Radiobiology*. – 5th ed. – Boca Raton: CRC Press, 2018. – DOI: 10.1201/9780429434649

4. Podgorsak E. B. *Radiation Physics for Medical Physicists*. – Berlin: Springer, 2010. – DOI: 10.1007/978-3-642-00875-7

5. International Atomic Energy Agency. *Radiation Oncology Physics: A Handbook for Teachers and Students*. – Vienna: IAEA, 2005.

6. Fowler J. F. Fast Neutron Therapy: Past, Present and Future // *Radiotherapy and Oncology*. – 2001. – Vol. 60(3). – P. 223–234. – DOI: 10.1016/S0167-8140(01)00348-2

7. Durante M., Loeffler J. S. Charged particles in radiation oncology // *Nature Reviews Clinical Oncology*. – 2010. – Vol. 7. – P. 37–43. – DOI: 10.1038/nrclinonc.2009.183

8. Suit H. et al. Clinical applications of fast neutron therapy // *International Journal of Radiation Oncology Biology Physics*. – 1992. – Vol. 23. – P. 599–606.

9. Paganetti H. *Proton Therapy Physics*. – Boca Raton: CRC Press, 2012. – DOI: 10.1201/b15461