FORMATION OF THE NEUTRON FLUX SPECTRUM FOR BORON NEUTRON CAPTURE THERAPY

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Abstract

Boron Neutron Capture Therapy (BNCT) is a promising radiation treatment modality based on the selective accumulation of boron-containing compounds in tumor cells followed by irradiation with a neutron beam. The therapeutic effectiveness of BNCT strongly depends on the characteristics of the neutron flux spectrum, including neutron energy distribution, flux intensity, and the ratio of thermal, epithermal, and fast neutron components. The formation and optimization of an appropriate neutron spectrum are therefore essential for achieving an effective therapeutic dose in tumor tissues while minimizing radiation exposure to healthy organs. This article examines the main principles of neutron flux spectrum formation for BNCT and discusses the influence of neutron energy on the physical and radiobiological characteristics of the treatment process. Particular attention is given to neutron moderation, spectral shaping, beam filtration, and optimization of the neutron beam for clinical applications. The study highlights the importance of selecting suitable moderator and filter materials to obtain an epithermal neutron beam with appropriate intensity and low contamination by fast neutrons and gamma radiation. The results of the analysis can contribute to the development and optimization of neutron beam shaping systems for improving the safety and therapeutic efficiency of BNCT.

Keywords

Boron Neutron Capture Therapy (BNCT); neutron flux; neutron spectrum; epithermal neutrons; thermal neutrons; fast neutrons; neutron moderation; neutron

beam shaping; neutron filters; radiation therapy; boron-10; neutron beam optimization.

Introduction

Boron Neutron Capture Therapy (BNCT) is an advanced form of radiation therapy that combines the selective delivery of boron-containing compounds to tumor cells with irradiation by a suitable neutron beam. The fundamental principle of BNCT is based on the interaction between the stable isotope boron-10 (^10B) and low-energy neutrons. When ^10B captures a neutron, it undergoes a nuclear reaction that produces an alpha particle and a lithium-7 nucleus. These high-linear-energy-transfer (LET) particles have a very short range in biological tissue, allowing radiation energy to be deposited predominantly within or close to boron-loaded tumor cells. This mechanism provides BNCT with the potential for selective destruction of malignant cells while reducing damage to surrounding healthy tissue.

The therapeutic effectiveness of BNCT is strongly dependent on the physical characteristics of the neutron beam. In particular, the neutron flux spectrum plays a significant role in determining the distribution of absorbed radiation dose within the patient. A useful BNCT beam generally requires an appropriate combination of thermal, epithermal, and fast neutrons. Thermal neutrons have a high probability of interaction with ^10B; however, their penetration depth in tissue is relatively limited. Epithermal neutrons, in contrast, can penetrate deeper into tissue and gradually lose energy through scattering processes, becoming thermalized at greater depths. Therefore, epithermal neutron beams are of particular interest for the treatment of tumors located at clinically relevant depths.

The formation of an appropriate neutron spectrum requires careful selection of the neutron source, moderator, reflector, filter, and other components of the beam-shaping assembly. The moderator is used to reduce neutron energies, while filters can suppress undesirable portions of the spectrum, particularly excessive fast-neutron and gamma-ray components. The optimization of these elements is necessary to obtain

sufficient neutron intensity while maintaining acceptable beam quality and minimizing unwanted radiation exposure.

The objective of this study is to investigate the principles of neutron flux spectrum formation for BNCT and to evaluate the influence of neutron moderation and spectral shaping on the main characteristics of the therapeutic beam. Particular attention is given to the formation of an epithermal neutron spectrum suitable for biomedical applications and to the optimization of beam parameters that can improve the therapeutic potential of BNCT.

Research Methodology

The methodology of this study is based on a theoretical and computational analysis of neutron flux spectrum formation for BNCT. The main stages of the research include the analysis of neutron production, neutron moderation, spectral shaping, and evaluation of the resulting beam characteristics.

First, the physical requirements for a BNCT neutron beam were analyzed. The neutron spectrum was considered in terms of three principal energy regions: thermal neutrons, epithermal neutrons, and fast neutrons. Particular attention was given to the epithermal energy range because neutrons in this region provide a compromise between sufficient tissue penetration and subsequent thermalization within the target volume.

The second stage involved analyzing the principles of neutron moderation. When high-energy neutrons pass through a suitable moderator, they lose energy through elastic and inelastic scattering processes. Hydrogen-containing materials are particularly effective moderators because of the relatively large energy transfer that occurs during neutron–hydrogen collisions. The selection of moderator material and its thickness directly influences the resulting neutron energy distribution and beam intensity.

The third stage consisted of evaluating the effect of spectral filters and beam-shaping components. Filters are introduced to reduce undesirable neutron components and gamma radiation. The effectiveness of the beam-shaping system was assessed by considering parameters such as epithermal neutron flux, fast-neutron contamination, thermal-neutron contribution, and gamma-ray contamination.

For quantitative evaluation, the neutron flux spectrum can be represented as a function of neutron energy:

where $\phi(E)$is the differential neutron flux and Φis the total neutron fluence. The total neutron flux can subsequently be obtained by integration over the relevant energy interval:

The quality of the neutron beam was evaluated using a set of physical parameters, including neutron flux, spectral distribution, neutron-to-gamma ratio, fast-neutron contamination, and the relative contribution of thermal and epithermal neutrons. These parameters are important for determining whether the generated beam is appropriate for BNCT applications.

The final stage of the methodology involved comparing different spectral-shaping conditions and identifying configurations that provide a sufficiently intense epithermal neutron component while reducing undesirable fast-neutron and gamma-ray contributions. Such an approach makes it possible to determine the optimal characteristics of the neutron beam for further application in BNCT treatment systems.

Research Results

The analysis demonstrates that the neutron flux spectrum is one of the most important physical factors determining the effectiveness of BNCT. The distribution of neutron energies directly affects neutron penetration into biological tissue, the rate of neutron thermalization, and the probability of ^10B(n,α)^7Li reactions within the tumor region.

The results indicate that an unmoderated neutron beam containing a significant fraction of high-energy neutrons is not optimal for direct BNCT applications. Fast neutrons can contribute to unwanted radiation dose through nuclear interactions with tissue and may increase the dose delivered to healthy organs. Therefore, spectral shaping is necessary to reduce the fast-neutron component and increase the relative contribution of neutrons in the epithermal energy region.

The use of an appropriate moderator results in a substantial shift of the neutron spectrum toward lower energies. As the moderator thickness increases, the average neutron energy decreases, while the fraction of thermal and epithermal neutrons increases. However, excessive moderation can lead to an undesirable reduction in the useful epithermal neutron flux because a large proportion of neutrons may become thermalized before reaching the treatment field. Consequently, moderator thickness must be optimized rather than maximized.

The analysis also demonstrates the importance of neutron filtering. Properly selected filter materials can reduce unwanted high-energy neutron components and gamma radiation while preserving a clinically useful epithermal neutron flux. The resulting spectrum should provide sufficient neutron intensity at the treatment aperture and appropriate penetration into tissue.

From a therapeutic perspective, an optimized epithermal spectrum provides several advantages. Epithermal neutrons can penetrate deeper into tissue than thermal neutrons and subsequently undergo moderation within the body. This process increases the probability that thermal neutrons will be available at the tumor location, where they can interact with accumulated ^10B and initiate the desired nuclear reaction.

The results further indicate that optimization of the neutron beam should not be based solely on maximum neutron flux. A high total flux does not necessarily correspond to improved therapeutic performance if it is accompanied by excessive

fast-neutron or gamma-ray contamination. Therefore, the spectral composition and radiation quality of the beam must be considered simultaneously.

Overall, the obtained results confirm that the formation of a suitable neutron flux spectrum requires an integrated optimization of the moderator, filter, reflector, and beam-shaping assembly. The most favorable configuration is characterized by a sufficiently high epithermal neutron flux, limited fast-neutron contamination, low gamma-ray contamination, and an appropriate thermal-neutron component. These characteristics are essential for achieving a balance between effective tumor irradiation and protection of healthy tissues in BNCT.

Conclusion

The study demonstrates that the formation and optimization of the neutron flux spectrum is a fundamental component in the development of effective Boron Neutron Capture Therapy (BNCT) systems. The therapeutic performance of BNCT depends not only on the total neutron flux but also on the energy distribution of neutrons within the treatment beam. In particular, the formation of an appropriate epithermal neutron component is essential for achieving sufficient penetration into biological tissue and subsequent thermalization in the tumor region.

The analysis showed that neutron moderation plays a key role in controlling the energy distribution of the beam. An appropriate moderator can reduce the energy of source neutrons and increase the contribution of neutrons within the epithermal region. However, excessive moderation may reduce the useful epithermal neutron flux by converting a considerable fraction of neutrons into the thermal energy region. Therefore, the thickness and material composition of the moderator should be carefully optimized.

The results also indicate that beam-shaping and filtering components are important for reducing undesirable fast-neutron and gamma-ray contamination. A high-quality BNCT beam should provide a sufficiently high epithermal neutron flux

while maintaining low contributions from unwanted radiation components. This balance is important because increasing the total neutron flux alone does not necessarily improve therapeutic effectiveness and may increase the radiation dose to healthy tissues.

The neutron energy spectrum also influences the radiobiological characteristics of BNCT. Since the energy distribution of the beam affects the relative contribution of different dose components, optimization of the neutron spectrum is directly related to the therapeutic ratio of the treatment. Previous radiobiological studies have similarly emphasized the importance of neutron energy spectrum and the different biological effects associated with thermal, epithermal, and fast neutron components.

Therefore, the optimal design of a BNCT neutron beam should consider the neutron source, moderator, reflector, filter, and beam aperture as an integrated system. The principal objective should be the generation of an intense and stable epithermal neutron beam with minimized fast-neutron and gamma-ray contamination. Further computational and experimental investigations, including Monte Carlo simulations and experimental neutron-spectrum measurements, are recommended for optimizing specific beam-shaping configurations and improving the clinical applicability of BNCT.

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