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Boron neutron capture therapy and environmental health

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Abstract

Boron Neutron Capture Therapy (BNCT) is an innovative cancer treatment modality that exploits neutron beams to specifically destroy malignant cells. Despite its assuring clinical benefits, BNCT familiarizes itself with unique environmental health considerations, including radiation safety, waste supervision, and potential ecological ramifications. This review investigates these aspects by appraising radiation safety protocols, waste disposal procedures, and environmental monitoring implementations associated with BNCT facilities. Effective radiation shielding and demanding safety protocols are necessary to protect occupational and public health from potential neutron radiation exposure. Waste management implementations must inscribe the treatment, handling, and disposal of radioactive and biological waste to anticipate environmental contamination. Long-term ecological monitoring is decisive for detecting and mitigating any adverse influences on surrounding ecosystems. The review also emphasizes the significance of public awareness and education in addressing environmental health concerns. By integrating case studies from various international perspectives and recognizing research gaps, this review aims to contribute comprehensive insights into the ecological health suggestions of BNCT and propose strategies for enhancing its sustainability. The findings accentuate the need for continuous improvement in safety measures, waste management, and public engagement to corroborate that BNCT can be safely and effectively implemented in a technique that protects both human health and the environment.

Key words: boron neutron capture therapy (BNCT), environmental health, radiation safety, waste management, radiation shielding

Introduction

Boron Neutron Capture Therapy (BNCT) is a breakthrough form of cancer treatment that manipulates the unique nuclear reaction between boron-10 and thermal neutrons to selectively destroy tumour cells (Malouff et al., 2021). BNCT requires administering a boron-containing compound to a patient, which preferentially accumulates in malignant tissues. Subsequently, the patient is exposed to a neutron beam, which interrelates with the boron, leading to a nuclear reaction that generates high-energy alpha particles and lithium nuclei (Monti Hughes & Hu, 2023) (fig. 1). These particles are highly annihilating to the targeted tumour cells while depreciating impairment to surrounding healthy tissues. BNCT is specifically assured for treating malignant brain tumours, head and neck cancers, and recurrent or resistant tumours that are less responsive to conventional therapies (Shen et al., 2024).

Environmental health apprehensions related to BNCT stem from the nature of neutron radiation and the operational requirements of BNCT facilities. Different from traditional X-ray-based treatments, BNCT requisites neutron sources, which constitute different challenges in terms of radiation safety and environmental impact. The presence of radioactive materials, the potential for accidental releases, and waste management are expository issues that must be addressed to corroborate both the safety of patients and the broader community.

Radiation safety in BNCT

Radiation sources and exposure

BNCT facilities utilize neutron sources, such as accelerators or nuclear reactors, to manufacture the necessary neutron beams for therapy (Jin et al., 2022). These sources produce neutron radiation, which can constitute risks if not legitimately managed. The primary exposure risk in BNCT comes from the neutron beam itself, which requires careful control and shielding to anticipate accidental exposure to patients, staff, and the public. Furthermore, neutron activation of materials within the facility can lead to secondary radiation, adding a layer of complexity to radiation safety protocols (IAEA-TECDOC-1223, 2001).

Safety protocols and measures

Ensuring radiation safety in Boron Neutron Capture Therapy (BNCT) requires a multi-faceted approach that incorporates advanced safety protocols and meticulous oversight. An expository aspect of this process requires the design and maintenance of tremendously effective shielding systems around neutron sources. These systems must be engineered utilizing specialized materials, such as boron-containing compounds and heavy metals such as lead, which can absorb or attenuate neutron and gamma radiation efficaciously (Gokul et al., 2023).

Additionally, the facility layout plays a significant role in minimizing radiation exposure. This necessitates strategic placement of treatment rooms, control rooms, and other operational areas, certifying that radiation exposure to medical personnel and the public is kept as low as reasonably achievable (ALARA) (Niu, 2011). Facility design must adhere to national and international radiation safety standards, including those established by the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), and local regulatory bodies. These standards contribute a comprehensive framework for radiation protection, circumscribing everything from the construction of the facility to the operational procedures utilized within it (EC et al., 2014; (WHO, 2021).

In addition to physical safety measures, the application of personal protective equipment (PPE) for staff is required. PPE, such as lead aprons, thyroid shields, and dosimeters, should be used routinely to monitor and diminish occupational exposure (Rose & Rae, 2019). Regular and systematic monitoring of radiation levels within the facility is also critical. This incorporates the manipulations of dosimeters to track cumulative radiation exposure for individuals and area monitors to evaluate environmental radiation levels in real time (Qureshi et al., 2022).

Occupational and public safety

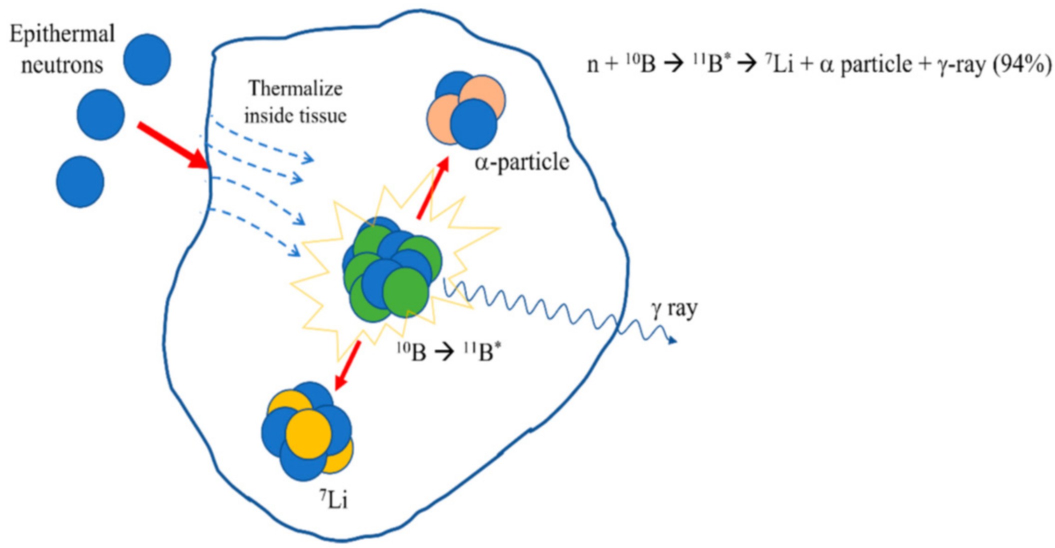

Fig. 1. Illustrative of the nuclear reaction between 10B atom and a thermal neutron (Monti Hughes & Hu, 2023)

Occupational safety for healthcare workers in BNCT requires regular training and adherence to safety guidelines to anticipate exposure to neutron radiation. This incorporates using dosimeters to monitor individual exposure levels and implementing safety measures such as restricted access areas and remote operation of neutron sources (Caruso, 2010). For public safety, facilities must certify that any potential radiation leaks are detected and addressed directly. Public communication strategies are essential for acquainting nearby communities about safety measures and any potential risks corresponding with BNCT operations (Isbn et al., 1985).

Waste management in BNCT facilities

Types of waste generated

Boron Neutron Capture Therapy (BNCT) facilities generate a complex array of waste types that necessary careful management to confirm both environmental safety and public health. Among the most critical configurations of waste produced are radioactive materials, which are formulated from neutron sources, contaminated equipment, and personal protective gear utilised during treatment procedures. Neutron source materials, once they have been depleted or rendered inactive, become radioactive waste that must be handled with extreme caution (Murray, 1981). This waste often accommodates long-lived radionuclides that can constitute significant environmental and health risks if not appropriately managed. Contaminated equipment and protective clothing, which may be exposed to radiation in the course of treatment, also contribute to the radioactive waste stream (Forsberg, 2003).

In addition to radioactive waste, BNCT facilities produce biological waste, which incorporates tissues, fluids, and other biological materials (blood samples, Urine samples, Saliva, Skin Biopsies, Surgical Specimens, and Cell Cultures) from patients undergoing treatment (Sauerwein et al., 2009). This biological waste can become contaminated with radioactive isotopes used in BNCT, such as boron-10, which, when activated by neutron capture, produces alpha particles and lithium nuclei. These secondary products are highly localized and dominant forms of radiation that can make biological waste hazardous. The contamination of biological waste poses unique challenges, as it requires specialized handling and disposal methods to anticipate radiation exposure to waste management personnel and the public, besides abstaining from environmental contamination (Singh et al., 2024).

Proper classification and segregation of waste types are indispensable steps in managing BNCT waste. Radioactive waste must be designated based on its radioactivity level, half-life, and the type of radionuclide present (Status and Trends in Spent Fuel and Radioactive Waste Management, 2022; Text et al., 2004; Department of Energy and Climate Change (DECC) and the Nuclear Decommissioing Authority, 2010). This classification contrives the appropriate handling, storage, and disposal methods. High-level radioactive waste, for example, may require containment in a shield, obtain storage facilities designed to isolate the waste for elongated periods, while low-level waste might be appropriate for disposal in designated landfills under controlled circumstances (Daw & Williams, 1977). Biological waste must be treated as both medical and radioactive waste, necessitating incineration or burial in facilities equipped to handle biohazards and radiation (Janik-Karpinska et al., 2023; Andeobu, 2020; Khan et al., 2010).

Waste disposal and treatment

The first step in the process is containment, where waste is securely enclosed to anticipate the release of radioactive particles into the environment. Containment often assumes using specialized containers to shield radiation and withstand environmental stresses over extended periods (Working Group on Design and Safety Analysis, 2023; Siskind et al., 1985).

Once contained, radioactive waste must be transported to facilities particularly designed for its disposal. The transportation procedures are governed by stringent regulations, ensuring that waste is moved safely and without risk of exposure to workers or the public. These regulations dominate the types of containers that can be used, the routes that can be grasped, and the monitoring that must be accomplished during transport (Barker, 1980). Upon arrival at specialized disposal sites, radioactive waste is frequently subjected to long-term storage in established facilities (Fentiman, 2009). These sites are engineered to separate radioactive materials from the biosphere and often manoeuvre deep geological repositories or engineered barriers that anticipate the migration of radionuclides (Marsh et al., 2021; Bennett, 2003; Mcfarlane et al., 2021). This extended period of storage is censorious for managing waste that comprehends long-lived radionuclides, which can remain hazardous for thousands of years (International Atomic Energy Agency, 2003).

In addition to containment and storage, BNCT facilities may employ diverse treatment techniques to lessen the volume or radioactivity of waste before disposal. Chemical decontamination is one such method, where waste materials are treated with chemical agents to amputate or neutralize radioactive contaminants (Gurau et al., 2023). This process can substantially reduce the radioactivity of waste, making it obvious and safer to manage. Another technique is immobilization, where radioactive waste is encapsulated in solid materials such as glass or cement (Barbhuiya et al., 2024). This process, known as vitrification or encapsulation, stabilizes the waste and counteracts the release of radionuclides, even if the storage container is compromised (Ojovan & Lee, 2011). Immobilization is exceptionally applicable for waste that is highly radioactive or that restrains radionuclides with long half-lives (Luhar et al., 2023; Li et al., 2021).

Facilities managing BNCT waste must adhere to conscientious protocols designed to anticipate contamination and assure the safe disposal of all waste compounds. These protocols are commonly based on national and international guidelines, such as those apparelled by the International Atomic Energy Agency (IAEA) and local regulatory authorities (Advances in Boron Neutron Capture Therapy, 2023). Compliance requires regular inspections, continuous monitoring of waste storage areas, and the implementation of safety measures such as redundant containment systems and emergency response plans. Staff must be disciplined in appropriate waste handling procedures, and the facility must maintain comprehensive records of all waste generated, processed, and disposed of. These records are clamorous for following the lifecycle of radioactive materials and ensuring that all waste is managed in correspondence with regulatory requirements(Magni et al., 2024).

Regulatory and compliance issues

In the United States, this responsibility falls under the apprehension of the Environmental Protection Agency (EPA), which sets forth regulations designed to manage radioactive and hazardous waste produced during BNCT procedures. The EPA's Resource Conservation and Recovery Act (RCRA) and the Atomic Energy Act (AEA) respectively govern the treatment, storage, and disposal of radioactive waste, certifying that BNCT facilities achieve within the bounds of federal environmental law (Osre, 2005; Act, 2011).

Correspondingly, in the European Union, BNCT facilities must adhere to regulations set by the European Atomic Energy Community (Euratom), which furnishes a comprehensive framework for the safe administration of radioactive waste. Euratom Directive 2011/70/Euratom pioneered the basic safety standards for the protection of the environment and the public from the possible hazards of ionizing radiation, which includes waste generated during BNCT (European Union, 2011). This directive mandates that each member state establish a national framework for radioactive waste management, ensuring that BNCT facilities meet strict safety criteria.

In Japan, the Nuclear Regulation Authority (NRA) reinforces the guidelines and regulations for radioactive waste management in BNCT (Forum, 2015). The Nuclear Regulation Authority certifies that BNCT facilities adhere to the standards set out in the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, which preside over the safe disposal of radioactive waste and the protection of the environment and public health.

In other regions, equivalent national bodies, such as the Canadian Nuclear Safety Commission (CNSC) in Canada and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in Australia, illustrate similar roles. These organizations are responsible for effectuating regulations that control the generation, treatment, and disposal of waste in BNCT facilities, associating their standards with international guidelines to ensure a high level of environmental protection (OECD, 2001; IAEA, 2019; Abstracts from the 44th Conference of the Australasian Radiation Protection Society, Held in Conjunction with the 5th International Symposium of the International Commission on Radiological Protection," 2020).

Potential environmental impacts

Environmental contamination

Key sources of contamination incorporate the accidental release of radioactive materials, which can occur due to equipment failure or human error (National Academies of Sciences Engineering Medicine, 2021). Additionally, the leakage of radioactive waste from storage facilities and the neutron activation of various constituents within the BNCT facility, such as structural materials and medical equipment, can lead to the release of radionuclides into the ecosystem (You et al., 2023; Capoulat & Kreiner, 2023). These contaminants may penetrate soil, water bodies, and the atmosphere, posing hazards to ecosystems and human health (You et al., 2024). To anticipate such occurrences, it is constitutive to appliance stringent containment measures, such as robust shielding, secure waste storage, and recently developed filtration systems (Lee & Cheong, 2020). Continuous monitoring of environmental radiation measures in and around BNCT facilities is pivotal (Wu et al., 2023). This monitoring should be administered using sensitive detection equipment proficient in identifying even low levels of contamination, and authorize for immediate intervention and mitigation measures to conserve the environment and public health (Silarski et al., 2023).

Long-term environmental monitoring

The long-term environmental monitoring of BNCT facilities is imperative for understanding and controlling their collision with the surrounding environment over extended periods. This necessitates the systematic collection and analysis of samples from diverse environmental matrices, which include soil, groundwater, surface water, and air, to detect any accumulation of radioactive substances (Management, 1999; Petisco-Ferrero et al., 2023). Such monitoring schemes should be comprehensive, engaging a scope of analytical techniques to measure both short-lived and long-lived radionuclides. The data collected should be circumspectly recorded and differentiated against historical baselines to identify tendencies and potential areas of apprehension. Long-term monitoring is not only about detecting contamination but also about understanding the environmental behaviour of radionuclides, including their transport, bioavailability, and prospective for bioaccumulation in local ecosystems. This knowledge is condemnatory for evaluating the all-inclusive environmental collision of BNCT operations and for aggregating informed decisions concerning facility management and regulatory conformity. Furthermore, the consequence of long-term monitoring should be transparently communicated to pertinent stakeholders, including regulatory bodies, local communities, and environmental organizations, to conserve public assurance and ensure accountability (Zhou et al., 2024; Nedunchezhian et al., 2016).

Mitigation strategies

Waste management implementation should be stringently designed to corroborate the safe handling, storage, and disposal of all radioactive waste products, including the use of containment systems that prevent discharge and spills. In addition to these preventative measures, BNCT facilities must evolve and regularly modernize emergency response plans that detail the stairway to be taken in the event of an accidental release. These plans should include instantaneous containment strategies, environmental cleanup protocols, and communication strategies to acquaint and safeguard the public (Li et al., 2012). Advances in neutron source technology, such as the development of neutron sources with lower activation potentials or more efficient shielding materials, make available encouraging avenues for reducing environmental risks. Regular rehearses and training for facility staff on knock-over response and containment measures are also critical to ensuring preparation and minimizing the impact of any accidental releases on the environment. By combining these mitigation strategies into the performance of BNCT facilities, it is feasible to significantly mitigate their environmental footprint and ensure the sustainability of this innovative cancer treatment modality (Chichester, 2012; IAEA, 2005; Abdullah et al., 2022).

Public health implications

Health risks to communities

The potential health risks constituted to communities residing near Boron Neutron Capture Therapy (BNCT) facilities primarily withstand radiation exposure, particularly from neutron sources utilized in the treatment process and from the handling and storage of radioactive waste. Although BNCT facilities are designed with meticulous safety protocols to minimize radiation exposure, there remains a necessity for continuous assessment and management of these risks to safeguard public health (Moss et al., 2001). This incorporates evaluating both the direct and indirect exposure pathways through which community members might come into contact with radiation. Direct exposure may be obtained through proximity to the facility, while indirect exposure could emerge from environmental contamination affecting air, water, or soil (Skwierawska et al., 2022; Al-Ibraheem et al., 2024; Wilson, 2000).

Health risk evaluations should incorporate a thorough analysis of radiation dose distributions in the surrounding areas, and consider account factors such as wind patterns, water flow, and the presence of local ecosystems that could expedite the spread of contaminants (Council, 2012; Series, n.d.; UTK, 1999). Additionally, it is essential to investigate the potential long-term health effects of low-dose radiation exposure, which may incorporate an increased risk of cancer, genetic mutations, and other radiation-induced diseases (Canet et al., 2022; Ali et al., 2020). By employing advanced modelling techniques and epidemiological studies, it is possible to forecast and quantify these risks more precisely. Furthermore, the effectiveness of safety measures, such as radiation shielding, containment systems, and emergency protocols, must be continuously evaluated and updated in light of new scientific findings and technological advancements (Rajendran et al., 2021; Ong et al., 2022). Collaborative attempts between BNCT facility operators, public health officials, and local communities are crucial in identifying and addressing any gaps in radiation protection strategies, thereby ensuring the health and well-being of those living near BNCT facilities (Matsumura et al., 2023; Sato et al., 2024).

Public awareness and education

Public awareness and education are fundamental constituents in the successful implementation of BNCT facilities, specifically concerning the environmental health implications related to this advanced cancer treatment modality. Educating the public about BNCT's benefits and risks assists in fostering an informed community that can immerse constructively with facility operators and regulators. Effective communication strategies should be customized to the specific needs and related to the local population, ensuring that information about radiation safety, potential health risks, and the protective measures in place are both approachable and comprehensible (Seneviratne et al., 2022; Schwint et al., 2019; World Health Organization, 2016).

Public awareness campaigns should leverage multiple platforms, which include social media, community meetings, and educational workshops, to reach a broad audience. These campaigns should not only provide information but also encourage dialogue, and acknowledging community members to voice their apprehensions and ask questions. Transparent communication about the safety protocols of BNCT facilities, the nature of radiation exposure, and the proceeding efforts to observe and mitigate any risks is essential in building trust (Kim, 2016). Additionally, targeted educational initiatives, such as school programs, have a critical role in heightening awareness among younger generations, helping to discover radiation and its applications in medicine (Pandit & Vinjamuri, 2014; OECD, 2010).

By incorporating feedback from the community, BNCT facilities can continuously enhance their communication strategies, ensuring that they address the most critical concerns and provide reassurance about the safety of the technology (Sauerwein et al., 2023). Furthermore, collaborations with local health departments, environmental agencies, and non-governmental organizations can magnify the reach and impact of these educational efforts, eventually contributing to a more informed and resilient community. Through sustained public awareness and education initiatives, it is attainable to ensure that communities are well-prepared to appreciate and support the safe operation of BNCT facilities, while also being vigilant and responsive to any potential health risks (Kiyanagi, 2018; Al-Bader et al., 2023; Seneviratne et al., 2023).

Future directions and research needs

Emerging technologies

The continued advancement of Boron Neutron Capture Therapy (BNCT) technology confines significant promise for minimizing the environmental and public health impacts associated with its utilization. Emerging technologies, such as next-generation neutron sources, provide the potential for more efficient and targeted delivery of therapeutic radiation, thereby reducing unintended radiation exposure to surrounding healthy tissues and the broader environment (Coghi et al., 2023; Mushtaq et al., 2023). These advancements could lead to significant reductions in the activation of facility constituents and the generation of radioactive waste, addressing some of the most crucial environmental concerns related to BNCT.

Additionally, innovations in treatment planning systems, driven by advancements in artificial intelligence and computational modelling, could capacitate more accurate control over neutron beam parameters, optimizing the balance between therapeutic efficacy and safety (Krishnamurthy et al., 2022; Monti Hughes & Hu, 2023). These systems could consolidate real-time monitoring and feedback mechanisms, acknowledging dynamic adjustments during treatment to certify that radiation doses remain within safe limits (Huang et al., 2023). Additionally, research into newly discovered materials for radiation shielding, particularly those with enhanced neutron-absorbing properties, could further mitigate the risk of environmental contamination (Gencel et al., 2021).

Policy recommendations

To certify the safe and sustainable operation of BNCT facilities, it is imperative to evolve comprehensive policy recommendations that communicate both current challenges and future requirements. Policies aimed at enhancing environmental health in BNCT facilities should focus on several key areas, including regulatory enhancement, the promotion of finest practices, and the reinforcement of ongoing research initiatives. Regulatory frameworks must advance to incorporate the latest scientific comprehensions of radiation safety and environmental protection, ensuring that BNCT facilities are held to the highest standards.

Policy recommendations should be recommended for the adoption of advanced technologies and implementations that depreciate radiation exposure and waste generation. This includes establishing stringent limits on permissible radiation levels, enforcing conscientious waste management protocols, and requiring regular environmental monitoring and reporting. Additionally, policies should encourage transparency and public engagement, corroborating that communities are sophisticated about the safety measures in place and the potential risks associated with BNCT.

Supporting research initiatives through targeted funding and collaborative partnerships is also a critical component of effective policy development. Policymakers should prioritize research that addresses the most significant environmental and public health challenges associated with BNCT, such as developing safer neutron sources, improving waste disposal methods, and assessing long-term health outcomes. By fostering an environment of innovation and accountability, policy recommendations can help ensure that BNCT facilities operate in a manner that protects both public health and the environment, while also advancing the field of cancer treatment (Dai et al., 2022; Suzuki, 2020; Zhang et al., 2023).

Research gaps

Identifying and communicating research gaps in the intersection of BNCT and environmental health is a prerequisite for driving future advancements and guaranteeing the long-term safety and sustainability of BNCT applications. One critical area where additional research is required is in the acknowledgement of environmental contamination risks associated with BNCT facilities. This incorporates studying the potential pathways through which radioactive materials might escape into the environment and evaluating the long-term ecological and health impacts of such contamination.

Further research is also required to develop more efficacious waste management techniques that can safely handle the radioactive by-products of BNCT. Advancements in waste treatment and disposal, such as modern containment systems or novel methods for reducing the half-life of radioactive materials, could significantly mitigate the environmental risks related to BNCT operations. Moreover, there is a necessity for longitudinal studies that evaluate the long-term health impacts of low-dose radiation exposure on communities working adjacent to BNCT facilities. These studies could provide valuable insights into the cumulative effects of radiation exposure and acquaint the development of more protective safety standards.

Discussion

The exploration of environmental health considerations in Boron Neutron Capture Therapy (BNCT) highlights several critical areas where further awareness is required to certify safe and sustainable applications. BNCT offers an assuring treatment for cancer, but its unique operational requirements and potential environmental effects necessitate a comprehensive approach to radiation safety, waste management, and public health.

Radiation safety

One of the principal concerns in BNCT is the management of neutron radiation. Effective radiation shielding and safety protocols are pivotal to reducing exposure to both healthcare workers and the public. Despite modernizations in shielding materials and safety technologies, the complexity of neutron interactions constitutes ongoing challenges. The review underscores the significance of meticulous adherence to regulatory standards and continuous monitoring to anticipate accidental exposure.

Waste management

BNCT facilities generate radioactive and biological waste that requires studious handling and disposal. The review discloses that while current waste management practices are vigorous, there is always room for improvement. Innovative waste treatment technologies and strategies to minimize waste generation could strengthen environmental safety. For example, advancements in waste immobilization and decontamination methods may provide more systematic solutions for managing radioactive waste.

Environmental impact

The potential environmental effects of BNCT facilities, including contamination from accidental releases and neutron activation, necessitate vigilant monitoring and mitigation efforts. The review emphasizes the necessity for comprehensive environmental monitoring programs that include regular sampling and analysis of soil, water, and air. Implementing advanced monitoring technologies and establishing long-term tracking systems can assist to detect and address environmental contamination promptly.

Public health implications

The health risks to communities adjacent to BNCT facilities are a significant concern. Efficacious public communication and education about radiation safety and facility operations can aid in alleviating public apprehensions and strengthen community trust. The review highlights the significance of transparent reporting and community engagement to address concerns and provide precise statistics about safety measures.

Comparative analysis and case studies

The review's comparative analysis of international BNCT practices and case studies provides valuable perceptions into diversified approaches to environmental health management. Lessons grasped from different regions can inform best practices and escort improvements in other facilities. For instance, facilities in countries with advanced BNCT programs have implemented innovative technologies and practices that could serve as models for other regions.

Future directions

Addressing the identified research gaps and exploring emerging technologies will be necessary for advancing BNCT practices. Areas for further research consist of developing new materials for radiation shielding, refining waste treatment techniques, and strengthening environmental monitoring systems. Collaboration between researchers, policymakers, and BNCT practitioners will be pivotal in advancing the field and ensuring the safe and sustainable implementation of BNCT.

Conclusion

Summary of key findings

The review highlights the critical environmental health considerations related to BNCT, including radiation safety, waste management, and potential environmental impacts. Key findings emphasize the significance of implementing effective safety measures, controlling waste responsibly, and monitoring environmental effects to guarantee the sustainability of BNCT facilities.

Implications for BNCT practice

The implications for BNCT practice necessitate acquiring best practices for environmental health management, enhancing safety protocols, and addressing public concerns. By focusing on these areas, BNCT facilities can intensify their operations and contribute to better environmental and public health outcomes.

Final thoughts

Addressing environmental health considerations in BNCT is essential for the responsible and sustainable implementation of this promising cancer therapy. Continued research, effective policies, and public engagement are pivotal for certifying that Boron Neutron Capture Therapy benefits patients while reducing potential negative impacts on the environment and public health.

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