Seminars in
NUCLEAR
MEDICINE

Implementation of Radiotheranostics: Challenges, Barriers, and IAEA-Driven Strategies for Sustainable Access

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Radiotheranostics represent a cutting-edge advancement in the management of noncommunicable diseases, integrating diagnostic imaging with targeted radiotherapy in a single, personalized approach. Over the past decade, the field has gained substantial momentum, with several radiopharmaceuticals now incorporated into clinical practice, most notably for neuroendocrine tumors and prostate cancer. The pipeline of novel agents continues to grow, offering promising therapeutic options for patients with cancers resistant to conventional therapies. Despite these advances, the broad implementation of radiotheranostics is impeded by several challenges, including logistical constraints, financial limitations, resource scarcity, political instability, and regulatory and educational barriers. Overcoming these obstacles requires coordinated mitigation strategies focused on strengthening education and training, expanding radiopharmaceutical production and development, enhancing research capacity, and establishing robust quality management systems. This review provides a comprehensive overview of the current global landscape of radiotheranostics, identifies key implementation barriers, and offers expert-driven strategies and recommendations from the International Atomic Energy Agency to support sustainable and equitable access to radiotheranostics.
Semin Nucl Med 55:1032-1044

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Funding: No funding source was used to support this work.
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 https://doi.org/10.1053/j.semnuclmed.2025.07.005
0001-2998/

Introduction

Radiotheranostics represents an innovative approach in nuclear medicine that integrates diagnostic and therapeutic modalities using the same molecular target.[1] This dual-function strategy employs complementary radiopharmaceuticals, initially for advanced molecular imaging, followed by targeted radionuclide therapy (TRT), thereby enabling improved clinical outcomes.[2] Radiotheranostics embodies the principles of precision medicine, leveraging molecular imaging to personalize treatment strategies based on specific biological characteristics.[3]

The global renaissance of nuclear medicine has been significantly driven by the rapid evolution and dissemination of radiotheranostic techniques.[4] This growth has been facilitated by breakthroughs in radiochemistry, radiobiology, and molecular imaging, alongside expanding applications in oncology, particularly in neuroendocrine tumors and metastatic prostate cancer. However, its potential use is not limited to oncology; exploratory applications in cardiovascular, inflammatory, and neurological disorders are underway, indicating a broader future role in personalized medicine.[4]

To ensure radiotheranostics can benefit diverse populations, there is an urgent need for an equitable and scalable implementation framework. The recently accepted World Health Organization (WHO) resolution WHA78.13 on strengthening medical imaging capacity underscores this necessity by advocating for global investment in medical imaging infrastructure. The Resolution highlights the essential role of medical imaging in timely disease detection and therapy, minimizing unnecessary surgical interventions, and optimizing complex medical treatments, including radiotheranostics.[5,6] As noncommunicable diseases now account for over 70% of global deaths, radiotheranostics could play a pivotal role in mitigating the burden of noncommunicable diseases by enabling earlier diagnosis, tailoring therapies, and optimizing clinical outcomes.[7] Effective imaging leads to earlier therapeutic decisions, reduces long-term healthcare expenditures, minimizes the need for invasive procedures, and ultimately improves patient quality of life. Furthermore, timely and appropriate therapy—guided by accurate imaging—not only improves clinical outcomes but also reduces the risk of disease progression and associated complications.[8]

Nevertheless, the transition from traditional, compartmentalized diagnostic and therapeutic models to integrated radiotheranostic workflows is fraught with challenges.[9] These barriers are heterogeneous and context-dependent, varying significantly across countries, continents, and healthcare systems. Key challenges include limited access to radionuclide production facilities, regulatory hurdles, insufficient workforce training, inadequate reimbursement structures, and geopolitical disparities in research investment and infrastructure.[9]

Understanding these multifactorial challenges, rooted in economic, regulatory, and operational domains, is essential to developing sustainable solutions. This review, conducted by a multidisciplinary panel of experts, consolidates current evidence and insights to map the critical impediments to radiotheranostic implementation. It also proposes strategic pathways to facilitate the broader adoption of this promising field, thereby ensuring that its benefits are globally realized.

Global Overview of Theranostics

Despite the growing recognition of theranostics, limited comprehensive evaluations have been conducted to assess its global status. One of the most robust resources in this domain is the IMAGINE database, developed by the International Atomic Energy Agency (IAEA) in 2019.[10] This database provides a global repository of data on radiotheranostic capabilities across more than 170 countries and territories, offering insights into infrastructure, technology distribution, and resource availability. It serves as a critical tool for identifying disparities in access, informing national health strategies, and promoting equitable development of nuclear medicine services.

Analysis of recent data from IMAGINE reveals significant heterogeneity in the availability and implementation of theranosticians across regions (Fig. 1). These disparities are largely driven by financial, political, and logistical constraints. According to the IMAGINE database, more than 131 countries have access to SPECT or SPECT/CT, with an estimated 23,488 systems in operation globally (Fig. 2). In contrast, 107 countries have PET/CT capabilities, with over 5381 PET/CT scanners installed (Fig. 3). However, these systems are distributed unequally. For instance, in high-income countries (HICs), a single SPECT scanner serves approximately 57,000 individuals, while in low-income countries, a single unit may serve as many as 33 million people. PET scanner distribution is even more disproportionate: one scanner serves around 250,000 people in high-income nations, compared to approximately 250 million individuals in low-income settings.[7]

Cyclotron infrastructure, essential for producing radiopharmaceuticals such as [^{18}F], is similarly uneven. As of 2023, more than 1500 cyclotrons are operational worldwide, with the majority (approximately 1400) operating below 25 MeV, and about 130 with higher energy ranges (25-70 MeV).[11]

A global survey conducted by the IAEA, published in *The Lancet Oncology* in November 2024, further explored access challenges.[12] A total of 105 countries participated in this surveillance study. The most widely utilized therapy was [^{131}I] for differentiated thyroid cancer, with approximately 250,000 treatments performed annually in 80 countries. Palliative therapies for bone metastases were available in about 60 countries, employing radionuclides such as [^{153}Sm]Sm, [^{89}Sr]Sr, [^{223}Ra]Ra, and [^{32}P]P, totaling approximately 45,000 treatments per year.[12] For neuroendocrine tumors (NETs), 39 countries reported approximately 43,000 targeted radionuclide therapies

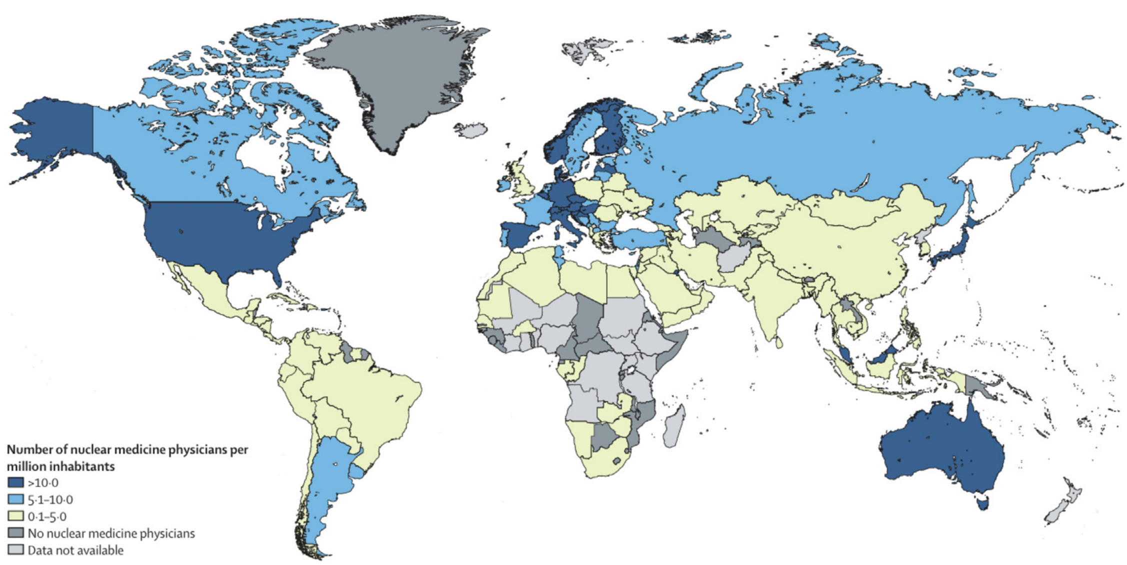

Figure 1 Global availability of theranosticians. Adapted from IMAGINE database (https://www.iaea.org/resources/hhc/nuclear-medicine/databases/imagine).

using [^{177}Lu]Lu-DOTATATE annually, while 30 countries performed around 1900 therapies using [^{131}I]MIBG. Moreover, [^{177}Lu]Lu-PSMA-based therapies for metastatic prostate cancer are being performed in 32 countries, with about 48,000 annual treatments. [^{225}Ac]Ac-PSMA treatments are available in 12 countries, totaling close to 1000 procedures annually. Liver radioembolization using microspheres is offered in only 10 countries, with around 24,000 procedures conducted each year.[12]

These findings underscore the dynamic and multifactorial nature of the global landscape in theranostics. The data highlight marked disparities in access, infrastructure, and regulatory capacity, reflecting both the progress and the significant challenges that continue to hinder the equitable implementation of this critical aspect of precision medicine.

Theranostics: Current Challenges

As previously stated, the current barriers to achieving excellence in theranostics arise from a complex interplay of logistical, resource-related, financial, political, educational, and regulatory constraints. The following sections will provide a domain-specific analysis of these challenges, highlighting key obstacles that hinder the optimal implementation and utilization of theranostic approaches (Table 1).

Resource-Related Challenges

Resource-related barriers continue to pose major challenges to the availability of theranostic services, particularly in low-

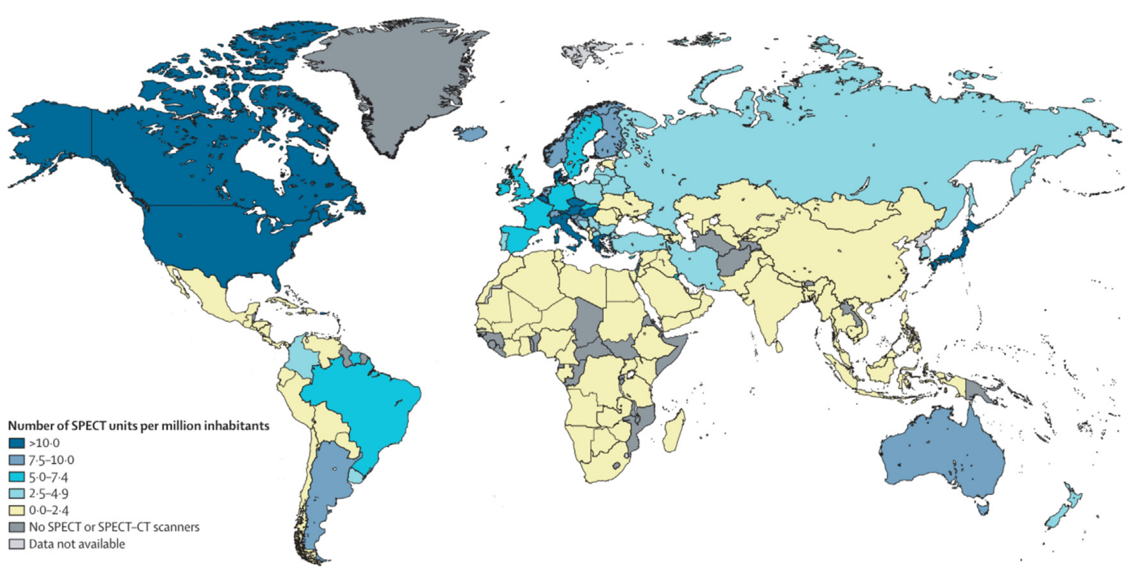

Figure 2 Global availability of SPECT scanners. Adapted from IMAGINE database (https://www.iaea.org/resources/hhc/nuclear-medicine/databases/imagine).

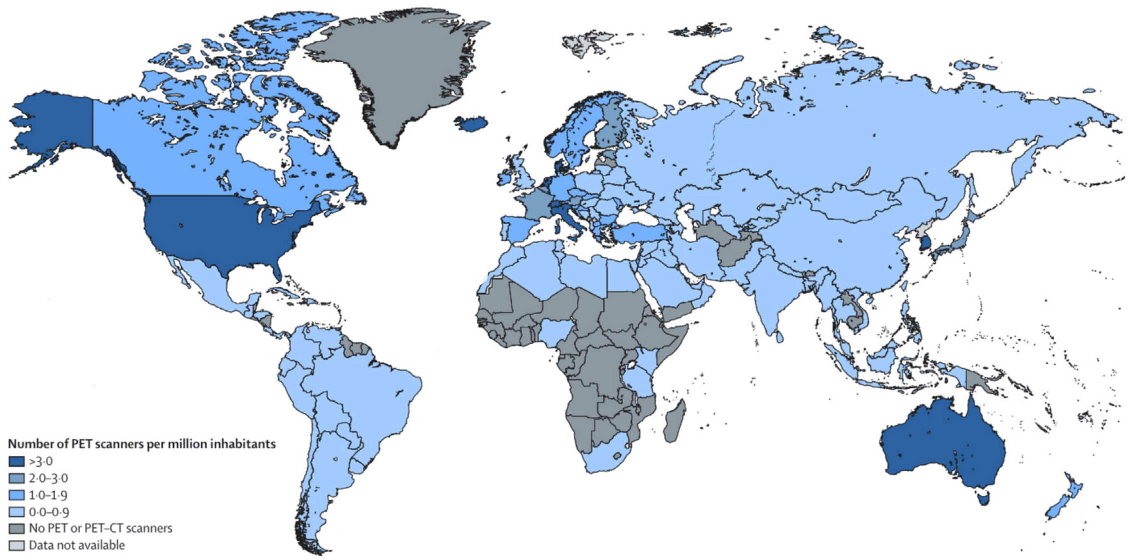

Figure 3 Global availability of PET scanners. Adapted from IMAGINE database (https://www.iaea.org/resources/hhc/nuclear-medicine/databases/imagine).

resource settings. Achieving equitable access to theranostics goes beyond the mere availability of facilities and equipment. It necessitates a multifaceted framework that incorporates not only technological infrastructure but also human resources, regulatory systems, and cultural factors.[13,14] This comprehensive framework can be analyzed using the "5 A's" model of healthcare access, which includes: Availability, Accommodation, Accessibility, Affordability, and Acceptability.

Availability

The availability of radiotheranostic services in low- and middle-income countries (LMICs) remains limited due to multiple interrelated barriers, predominantly stemming from infrastructure deficiencies. Advanced imaging modalities such as PET/CT scanners, cyclotrons, and SPECT cameras are essential components of nuclear medicine, yet are frequently inaccessible or inadequately maintained in these settings.[15] Existing nuclear medicine centers are often under-resourced, with compromised functionality owing to unreliable power supply, limited maintenance capabilities, and insufficient regulatory oversight. For example, cyclotrons required for the production of short-lived isotopes, such as $[^{18}F]F$, are exceedingly rare.[16] Additionally, longer-lived isotopes like $[^{131}I]I$ are frequently imported, introducing significant logistical delays and elevating associated costs. Theranostic radiopharmaceuticals, such as $[^{177}Lu]Lu$, are also inconsistently available, largely due to disruptions in global supply chains or restrictive import regulations.[17] Strategic investments in centralized tertiary referral centers and the adoption of cost-effective, portable technologies, such as solid-state SPECT detectors and compact cyclotrons, could substantially mitigate these equipment-related disparities.[18,19]

Human resource limitations further compound access issues. There is a marked shortage of qualified nuclear medicine professionals, including physicians, radiochemists, radiopharmacists, medical physicists, nurses, and technologists.[20,21] This shortage is exacerbated by the emigration of trained personnel to higher-income countries.[7,22,23]

Radiopharmaceutical manufacturing and supply present additional challenges.[24] Many LMICs depend heavily on imported radiopharmaceuticals, which are vulnerable to political instability, transportation delays, and inconsistent customs regulations. Local production is often unfeasible due to the absence of cyclotron or reactor infrastructure.[24,25]

Accommodation

Accommodating the diverse needs of patient populations in LMIC demands a multidimensional approach that encompasses flexible operational practices, culturally responsive communication, and infrastructure tailored to individuals with physical disabilities.[26] In many LMICs, the standard operating hours of nuclear medicine departments often conflict with the working schedules of patients who depend on daily wages, thus limiting their ability to attend scheduled appointments without incurring income loss.[26,27] Addressing this disconnect through extended or alternative scheduling may improve service accessibility.

Infrastructural inadequacies further compromise the delivery of radiotheranostic services. Frequent power outages, insufficient water supply, and the absence of appropriate waste management systems for radioactive materials collectively hinder the operational continuity and safety of nuclear medicine facilities.[28] Moreover, maintenance protocols are frequently underdeveloped, and medical equipment is often used beyond its optimal lifespan due to budgetary constraints. These conditions contribute to equipment malfunction, service interruption, and ultimately, a decline in patient trust and system efficiency. Ensuring infrastructure resilience and incorporating regular maintenance schedules are essential for sustaining reliable and safe radiotheranostic services in resource-constrained settings.

Table 1 Summary of Key Challenges in Radiotheranostic Practice and Delivery

Domain	Subdomain	Important and Challenging Aspects
Resource-related challenges		• Limited availability of advanced imaging equipment (PET/CT, cyclotrons, SPECT) in LMICs • Under-resourced nuclear medicine centers with unreliable power and maintenance • Shortage of qualified nuclear medicine professionals • Dependence on imported radiopharmaceuticals with supply chain vulnerabilities • Need for sustainable local training and international collaborations
	Accommodation	• Mismatch between department operating hours and patient work schedules • Infrastructural inadequacies (power outages, water supply, waste management) • Underdeveloped maintenance protocols and aging equipment • Impact on service continuity, safety, and patient trust
	Accessibility	• Urban-centric distribution of facilities, disadvantaging rural populations • High travel costs and poor transportation; limited global production capacity of radiopharmaceuticals • Weak referral networks causing delays and misdirected care • Dependence on aging reactors with risk of decommissioning
	Affordability	• High upfront and operational costs for equipment and training • Cost-shifting to patients due to limited public funding • Need for dedicated government funding and international support • Innovative cost-sharing and insurance models required for sustainability
	Acceptability	• Cultural misconceptions and fear of radiation • Barriers for women and marginalized groups • Need for community education and outreach • Inclusion in clinical guidelines to support acceptance
Logistical challenges		• Short half-lives of radiopharmaceuticals requiring rapid delivery • Vulnerability of global supply chains due to few production sites • Strict regulations for transport of radioactive materials • Need for decentralized local manufacturing to improve resilience
Financial challenges		• High costs of radiopharmaceuticals, infrastructure, and • Complex reimbursement systems not aligned with treatment value • Need for data on cost-effectiveness and patient outcomes • Lack of standardized reimbursement and service models globally
Political hurdles and conflicts		• Destruction of infrastructure due to conflict • Shortages of medical supplies and radionuclides • Brain drain of specialized healthcare professionals • Financial instability limiting investment and innovation
Regulatory challenges		• Complex multi-agency licensing and compliance requirements • Strict safety standards for handling radioactive materials • Need for ongoing personnel education and certification • Adapting regulations to novel agents and personalized approaches

Accessibility

Accessibility to radiotheranostic services in LMICs remains disproportionately skewed toward urban centers, where most nuclear medicine facilities are concentrated. This urban-centric distribution imposes considerable access barriers for populations residing in rural or remote areas. Patients in these regions often face prohibitive travel expenses, extended travel times, and the burden of navigating poorly developed transportation networks. These logistical and economic constraints not only limit physical access to care but also exacerbate existing health inequities by delaying diagnosis and treatment.[28,29]

The production of radiopharmaceuticals faces significant challenges due to the specialized expertise and equipment required, resulting in limited global capacity and an increased risk of shortages, especially for short-lived diagnostic isotopes.[30] Two main production methods exist: cyclotrons, which are cost-effective for certain isotopes (e.g., [^{18}F]F, [^{68}Ga]Ga), and nuclear reactors, which produce a broader range but pose safety and waste management issues. The choice between these methods depends on target isotopes, flexibility, and cost. Most therapeutic radioisotopes are produced in research reactors, but only about 30 of the world's 222 reactors have industrial-scale radionuclide production capability. The global supply relies on a handful of reactors in just eight countries, many of which face imminent decommissioning, threatening accessibility and hindering future availability.[31]

In addition to geographic barriers, systemic issues such as weak referral networks further undermine timely access to radiotheranostic services. Inefficient referral pathways may result in prolonged waiting periods, misdirected referrals, or transfers to centers that lack the requisite infrastructure and expertise.[32] These inefficiencies not only delay initiation of appropriate care but also contribute to patient attrition, loss to follow-up, and suboptimal clinical outcomes.

Affordability

Radiotheranostics is resource-intensive, with high upfront costs for equipment, infrastructure, and personnel training.[33] Beyond the initial outlay, sustained operational costs, including equipment maintenance, regulatory compliance, and robust quality assurance protocols, further compound the financial burden. In many LMICs, constrained public health funding often results in cost-shifting to patients, limiting access for large segments of the population.[34]

To address these systemic disparities, a comprehensive and strategically coordinated financing model is imperative. Governments must earmark dedicated funding for nuclear medicine within national health budgets to enable the establishment and long-term maintenance of core infrastructure, human resource development, and supply chains for essential isotopes and radiopharmaceuticals. In parallel, international development agencies and global health organizations are crucial in providing catalytic funding for infrastructure, training, research, and clinical service expansion.[35]

Innovative cost-sharing mechanisms can further support financial sustainability. Sliding-scale payment models, adjusted according to income, can reduce the direct cost burden on patients. The integration of nuclear medicine services into national health insurance schemes is vital, as is the promotion of private insurance models customized to the unique cost structures of radiotheranostic interventions. Microinsurance schemes targeted at underserved populations can enhance equity in coverage. Additionally, public-private partnerships offer an untapped yet promising avenue for shared investment and risk mitigation in service delivery. Ultimately, a resilient and equitable radiotheranostic ecosystem in LMICs will depend on the convergence of government commitment, international support, adaptable cost-recovery models, and inclusive insurance solutions. Such an integrated financial framework is essential to ensuring the scalability, accessibility, and long-term sustainability of nuclear medicine services in resource-limited settings.[36]

Acceptability

The acceptability of nuclear medicine procedures, including radiotheranostics, is profoundly influenced by cultural and social factors, particularly in LMICs. Public awareness and prevailing cultural attitudes play a critical role in shaping perceptions of nuclear medicine. Widespread misconceptions regarding radiation and nuclear technology can act as significant deterrents, discouraging patients from seeking radiotheranostic services. Additionally, cultural norms and societal expectations may impede access to care for specific demographics, such as women or marginalized groups, thereby exacerbating existing health disparities.[37]

Addressing these challenges requires proactive community engagement through targeted education and outreach initiatives. Such programs are essential for demystifying nuclear medicine, correcting misinformation, and fostering a more informed public discourse. Building trust within communities and ensuring robust processes for informed consent are particularly important in populations with limited prior exposure to nuclear medicine technologies. These efforts not only enhance acceptability but also contribute to the ethical delivery of care.

Furthermore, the formal incorporation of radiotheranostic applications into clinical practice guidelines, such as those developed by the National Comprehensive Cancer Network, the European Society for Medical Oncology, and through the establishment of appropriate use criteria, is vital for the sustained development and integration of these modalities. Such inclusion ensures that radiotheranostics are recognized as standard-of-care options, thereby supporting their broader acceptance and utilization within diverse healthcare settings.[38]

Logistical Challenges

Radiopharmaceutical supply chain logistics pose distinct and critical challenges, setting them apart from conventional pharmaceutical distribution. Due to the short physical half-lives of radiopharmaceuticals, timely coordination of production and rapid delivery to clinical sites is essential. Stockpiling is unfeasible, as radioactive decay quickly compromises both efficacy and safety, and even generator-based systems have limited operational lifespans. Global supply remains vulnerable due to overreliance on a small number of aging nuclear reactors and production facilities, often concentrated in specific geographic regions. Disruptions at these nodes, caused by technical failures, maintenance delays, or workforce shortages, can result in widespread shortages. This risk is amplified by the growing demand for radiotheranostic procedures and constrained production scalability.[39-41]

Transportation of radiopharmaceuticals is tightly regulated due to their radioactive nature. Classified as Class 7 hazardous materials, their shipment requires specialized licensing, secure packaging, radiation shielding, and compliance with detailed documentation and incident protocols.[42] Air transport is often essential to meet clinical timelines, further complicating logistics through added regulatory scrutiny. The centralization of production underscores the need for decentralized, local manufacturing solutions, such as hospital-based cyclotrons and generator systems, to improve supply chain resilience and might reduce reliance on imports. Countries lacking domestic production remain particularly susceptible to international supply chain disruptions.[43,44]

Radiopharmaceutical shortages should be treated as clinical emergencies, requiring predefined mitigation strategies and coordinated responses by regulatory authorities. Strengthening domestic manufacturing, harmonizing regulatory procedures, and fostering public-private partnerships are essential steps toward building a secure and sustainable supply infrastructure.

Financial Challenges

The field of radiotheranostics faces significant challenges related to financial investment, service delivery, and reimbursement frameworks. One major obstacle is the substantial direct and indirect costs associated with implementing these advanced therapies, including expenses for radiopharmaceuticals, specialized infrastructure, and highly trained personnel. The complexity of reimbursement systems further complicates the adoption of radiotheranostics, as existing models often struggle to account for the multifaceted nature of these treatments, encompassing not only drug costs but also administration, dosimetry, imaging, and ongoing patient monitoring.[45-47] In this context, building models that promote the self-sustainability of nuclear medicine services—through efficient resource use and integration into national health systems—is essential for long-term viability.

A key challenge lies in aligning reimbursement with the actual value delivered to patients, as traditional fee-for-service models may incentivize volume over quality. The shift toward value-based medicine introduces additional hurdles, such as the need for robust data on patient-reported outcomes, cost-effectiveness, and long-term benefits, metrics that are not always readily available or easily measured in the context of novel radiotheranostic interventions. Evaluating cost-effectiveness using measures like Incremental Cost-Effectiveness Ratios and Quality-Adjusted Life Years requires comprehensive clinical and economic data, which can be difficult to obtain for new therapies.[48-50]

There are also large-scale economic and logistical challenges. While macroeconomic analyses suggest potential for significant returns on investment and reductions in cancer mortality, realizing these benefits requires coordinated action across government, private, and hospital sectors. The lack of standardized, sustainable reimbursement pathways and service models remains a barrier, particularly as international reimbursement structures vary widely and may not adequately support the full spectrum of radiotheranostic care.[4]

Professional organizations, such as the European Association of Nuclear Medicine, Society of Nuclear Medicine and Molecular Imaging, Nonstate Actors (like the World Federation of Nuclear Medicine and Biology and International Society of Radiology) and the IAEA, continue to highlight the complexity of establishing equitable access to radiotheranostics.[51] Persistent advocacy and cross-sector collaboration are needed to address these systemic challenges and ensure that patients can benefit from advances in radiotherapeutic technologies.

Political Hurdles and Conflicts

Political instability, armed conflict, and war significantly hinder the development and sustainability of radiotherapy and nuclear medicine services. These conditions often result in the destruction of critical infrastructure, including hospitals and specialized facilities, as exemplified in countries such as Iraq, Syria, and Yemen. The loss of physical infrastructure is further compounded by severe shortages of medical supplies and radio pharmaceuticals essential for diagnostic and therapeutic procedures.[28,52]

A recent surveillance study of West Asian countries demonstrated that politically stable nations exhibit significantly higher densities of professionals, such as physicians, technologists, medical physicists, and nurses, compared to their politically unstable counterparts.[53] These findings underscore the direct relationship between political stability and the availability of a specialized healthcare workforce.

In addition, political turmoil contributes to a substantial "brain drain" as highly skilled healthcare professionals, including nuclear medicine physicians and radiation oncologists, migrate to safer and more stable environments. This exodus exacerbates existing human resource shortages. Financial instability, frequently a byproduct of conflict, further restricts investment in medical technology and hinders the maintenance and modernization of existing systems, limiting the adoption of advanced modalities such as PET/CT and SPECT/CT.[28] Inconsistent funding also impedes local research and innovation, fostering dependence on costly imports. Collectively, these interlinked challenges severely reduce access to essential oncologic and diagnostic care, contributing to increased morbidity and mortality and a decline in overall public health outcomes.

Regulatory Challenges

The regulatory landscape of radiotheranostics is shaped by a complex interplay of national and international frameworks, each designed to ensure patient and staff safety while facilitating technological innovation. At the heart of these regulatory challenges lies the necessity for comprehensive facility licensing and compliance.[54] This means that any center intending to offer radiotheranostic services must adhere to stringent national radiation safety laws, which encompass the secure handling, storage, and disposal of radioactive materials. The process is not isolated to a single regulatory body; rather, it often involves cross-disciplinary oversight.[55] Health authorities, nuclear regulatory agencies, and sometimes even drug enforcement bodies collaborate to inspect, license, and periodically audit these centers. Such oversight is guided by well-established principles, such as those set forth by the IAEA, which emphasize a risk-based approach to safety and the harmonization of practices across jurisdictions.[56]

Within the facility, the regulatory scrutiny extends to the design and operation of quality control (QC) laboratories.[57,58] These labs are critical in ensuring the safety and efficacy of radiopharmaceuticals prior to clinical use. Regulatory requirements dictate that QC personnel must be equipped with appropriate shielding and remote handling tools, minimizing radiation exposure during hazardous procedures. The physical environment of these laboratories is also subject to architectural standards that mandate the use of radiation shielding materials, the segregation of radioactive waste streams, and the installation of real-time dosimetry systems to monitor exposure levels continuously.[57,58] These requirements are not static; they evolve in response to advances in radiotheranostic technology, emerging scientific evidence, and periodic updates to international guidelines.[59]

The regulatory challenges are compounded by the need for ongoing education and certification of personnel, the implementation of robust record-keeping systems, and the establishment of incident reporting mechanisms. Any deviation from established protocols can trigger regulatory intervention, ranging from corrective action plans to suspension of licensure.[38] Furthermore, as radiotheranostics increasingly involves novel agents and personalized approaches, regulatory agencies face the challenge of adapting existing frameworks to accommodate new risks and uncertainties. This dynamic environment demands a proactive and collaborative approach among stakeholders to ensure that regulatory measures remain both effective and enabling, fostering the safe and responsible advancement of radiotheranostic practices.

Effective Solution to Overcome Current Challenges

As part of the IAEA's vision to promote equitable and accessible radiotheranostic services globally, the following section outlines the core pillars, endorsed and supported by the IAEA, that are essential for overcoming current challenges and enabling the sustainable and prosperous implementation of radiotheranostic practices (Fig. 4).

Education and Training: A Cornerstone for Sustainable Radiotheranostics Implementation

The prosperous development of radiotheranostics is fundamentally intertwined with the challenges and opportunities presented by education and training. As the field rapidly evolves, the need for a harmonized, scalable, and internationally recognized educational framework becomes increasingly apparent. Structured and standardized training is not only a prerequisite for the safe and effective delivery of radiotheranostic therapies but also a driving force for innovation and the expansion of expertise. The IAEA has been instrumental in articulating guiding principles for education and practice, as reflected in its 2024 white paper, which delineates core competencies ranging from clinical decision-making and molecular radiopharmacy to internal dosimetry, radiation protection, and ethical medical practice. This framework is designed to be adaptable, addressing the diverse resource settings of both high-income and LMICs, thereby supporting equitable access to training.[38]

The IAEA's initiatives extend beyond theoretical instruction, encompassing regional training courses, hands-on fellowships, e-learning modules, and scientific exchanges that provide nuclear medicine professionals with practical experience in theranostic procedures and radiopharmaceutical production. These efforts are complemented by IAEA-coordinated research projects, which foster clinical research expertise and expand the scientific evidence base, particularly in areas where participation in industry-sponsored trials is limited. Despite these advances, sustainability remains a challenge, underscoring the need for integration of these educational opportunities into structured, competency-based curricula with defined milestones and international recognition.

Certification mechanisms, such as those established by the European Board of Nuclear Medicine and the Asian Nuclear Medicine Board, offer robust platforms for formalizing training pathways. The expansion of these mechanisms to include dedicated radiotheranostics certification, aligned with IAEA principles, would unify training standards, enhance practitioner mobility, and strengthen confidence among healthcare providers, regulators, and patients.[60] The Nonstate Actors working on the worldwide level can also certainly contribute to these efforts in collaboration with the IAEA.[61] The International Centers for Precision Oncology also contribute by offering modular curricula and standardized accreditation of theranostics centers, thereby reinforcing global training pipelines and facilitating knowledge transfer.[62,63]

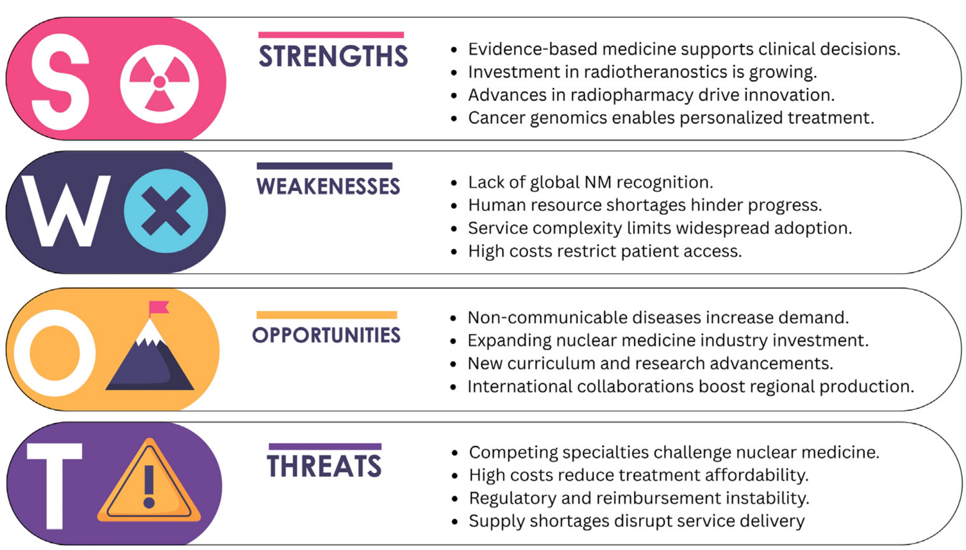

Figure 4 Visual summary of the main strengths, weaknesses, opportunities, and threats identified in radiotheranostics, based on a comprehensive review of current evidence.

In LMIC, capacity constraints such as limited infrastructure, a shortage of qualified trainers, and regulatory hurdles can impede progress. However, these challenges also present opportunities for innovation and partnership. The IAEA's Rays of Hope initiative exemplifies this approach by supporting anchor centers of excellence that serve as regional training hubs and catalysts for national and regional theranostic programs.[64,65] Experiential learning is emphasized as indispensable, with minimum procedural thresholds and interdisciplinary collaboration forming essential components of certification in various radiotheranostic applications.

Ultimately, education and training are not merely operational requirements but strategic enablers that bridge the gap between technological innovation and equitable access to care. By harmonizing curricula, integrating international certification, and leveraging the infrastructure of regional anchor centers, the global radiotheranostics community can cultivate a workforce that is competent, confident, and credentialed. The collective efforts of international organizations, nonstate actors, certification boards, professional societies, and collaborative networks are essential in establishing and upholding shared educational and training standards, ensuring that the promise of radiotheranostics is realized worldwide.

Quality Management

Ensuring safety and quality across the radiopharmaceutical lifecycle is essential. Any lapse in safety protocols or quality standards poses significant risks to patient health and may compromise trust in both diagnostic and therapeutic applications. Whether locally manufactured or centrally distributed, all radiopharmaceuticals must undergo rigorous QC and continuous surveillance to uphold the highest standards of care.[66]

The IAEA recommends the use of the Quality Assurance Audit for Nuclear Medicine Practices (QUANUM) checklist to guide best practices, particularly regarding radiopharmaceutical safety. QUANUM promotes the integration of comprehensive, patient-centered quality management into nuclear medicine services. It provides a standardized tool for conducting independent audits, evaluating all aspects of clinical and operational performance.[66-68]

Radiopharmacy and radiopharmaceutical QC are central components of the QUANUM audit process, reflecting their pivotal role in ensuring safe and effective practice. These audits aim to confirm that only radiopharmaceuticals meeting internationally accepted safety and quality standards are administered. The process encourages continuous quality improvement through corrective action plans and supports alignment with global best practices across all radiopharmaceutical-related activities.[67]

Research and Development: Advancing Radiotheranostics Research

As radiotheranostic agents continue to evolve, the necessity for robust international collaborative trial networks has become increasingly apparent. A globally coordinated research infrastructure is essential for the advancement of radiotheranostics and the refinement of personalized oncologic treatment strategies.[69] Recent clinical successes have catalyzed substantial investment in targeted radiopharmaceuticals, exemplified by pivotal phase 3 trials such as ALSYMPCA, NETTER, and VISION.[70-72] These landmark studies facilitated the regulatory approval of [^{223}Ra]$RaCl_2$, [^{177}Lu]Lu-DOTATATE, and [^{177}Lu]Lu-PSMA-617, respectively, and have established a precedent for the rigorous evaluation of radiopharmaceutical therapies.[70-73] The expanding evidence base and heightened engagement from the pharmaceutical industry have resulted in a notable increase in the number of active phase 3 studies, currently totaling 34, which are investigating both expanded indications for approved agents and novel compounds across diverse oncologic indications.

Despite these advances, the global cancer burden continues to escalate, with projections indicating that by 2032, nearly three-quarters of cancer-related mortality will occur in LMICs. However, the landscape of cancer research, particularly in radiotheranostics, remains disproportionately concentrated in HICs. This imbalance underscores the urgent need for context-specific research and clinical trials that address the unique cancer epidemiology, biological diversity, and healthcare infrastructure limitations characteristic of LMICs.[74]

Radiotheranostics research in LMICs is impeded by a constellation of interrelated challenges, including limited clinical research infrastructure, insufficient funding, and a deficit of adequately trained personnel.[7] Systemic barriers such as the lack of protected research time, underdeveloped cancer registries, and minimal governmental support further constrain research capacity. Ethical and regulatory challenges, characterized by inadequate oversight and complex approval pathways, compound these difficulties, while safety concerns persist in the absence of standardized protocols. Critically, populations in LMICs remain severely underrepresented in clinical trials, with no phase 3 studies of currently approved therapeutic radiopharmaceuticals conducted in these settings.[7]

Inclusion of LMICs in all stages of radiotheranostics research, spanning basic science, preclinical development, medical physics, radiopharmacy, and clinical investigation, is imperative for several reasons. Scientifically, data derived from HIC-based studies may lack generalizability due to genetic, environmental, and epigenetic differences; for example, African men experience disproportionately aggressive prostate cancer, yet remain underrepresented in global trials, limiting the applicability of findings and optimal sequencing of therapeutics. From an ethical perspective, it is essential that therapies tested in LMICs are accessible to these populations postapproval, ensuring global equity in cancer care. Operationally, LMICs offer advantages such as lower costs, higher disease prevalence, and large patient populations, which can facilitate accelerated recruitment and yield robust, generalizable data.

The IAEA has outlined strategic approaches to overcoming these barriers. Partnership models involving the IAEA, industry, academia, and professional societies are critical for building local research capacity and infrastructure. International initiatives, such as the IAEA's Rays of Hope and Anchor Centers, provide essential funding, training, and infrastructure support, while also aiming to harmonize data collection and generate real-world evidence through global research databases. The development of standardized clinical trial protocols and monographs tailored to radiopharmaceutical research is a further priority, enabling translation into clinical practice guidelines.[65] Capacity building efforts focus on the establishment of clinical trial sites, the training of nuclear medicine specialists, the strengthening of regulatory frameworks, and the assurance that all research adheres to Good Clinical Practice standards.[75]

Radiotheranostics holds substantial promises for addressing unmet medical needs, as evidenced by successful early-phase clinical trials and innovative research initiatives in LMICs. Key areas of innovation include the early and accurate diagnosis of complex cancers, the development of safer and more effective radiopharmaceutical therapies, the integration of theranostics to guide personalized treatment decisions, and the fostering of cross-disciplinary collaboration among medicine, chemistry, biology, and physics.

There is a compelling need to advocate for equitable and effective cancer care worldwide. Conducting radiopharmaceutical trials exclusively in HICs is no longer tenable; integrating LMICs into the global research ecosystem is both a scientific and ethical imperative. Future strategies should prioritize expanded participation of LMICs in phase 3 trials, the inclusion of LMIC experts in global health commissions, and the coordination of funding to support sustainable, context-driven research. Radiotheranostics is poised to transform cancer care, but its full potential can only be realized through inclusive global research efforts that address the needs of populations bearing the greatest burden of disease. Bridging these gaps through international collaboration, ethical and inclusive trial design, and sustained investment will be fundamental to achieving more effective and equitable cancer diagnostics and therapeutics.[76,77]

Bridging the Communication Gap Between Theranosticians and Promoting Physicians

The widespread acceptability and optimal utilization of nuclear medicine within the broader medical community are often underemphasized. Many medical specialties with shared patient interests demonstrate a limited perception of nuclear medicine procedures and therapeutic indications.[78] This includes a constrained understanding of appropriate use criteria and guidelines for radiotheranostics. This challenge is particularly pronounced in regions where the field of nuclear medicine is novel or still maturing. Consequently, it is imperative to actively promote awareness among referring physicians and oncologists to significantly enhance patient care and clinical practice by fostering a more comprehensive understanding of nuclear medicine's capabilities.[78]

Advocacy

To ensure the sustainable success of radiotheranostics in nuclear medicine, patient advocacy initiatives are imperative—this includes lobbying governments for reimbursements, supply chain logistics and/or regulatory approvals—for the service to be performed. Educational initiatives—for patients, clinicians, and politicians alike—also need to be addressed. This will require coordinated advocacy and lobbying by professional, patient, and philanthropic organizations involved in a specific disease type, for the best patient-centered outcomes.[79,80]

Amidst growing commercialization in radiotheranostics, the integration of social responsibility into industry practice is critical for preventing inequitable access.[81] Drawing lessons from the global rollout of HIV and HBV treatments—facilitated by access-oriented programs and legal frameworks—it is incumbent upon stakeholders to develop analogous pathways for theranostics. Initiatives, including transparent pricing, technology sharing, and coordinated access programs, can mitigate anticipated legal and economic barriers. Prioritizing social responsibility now is essential for preempting widening disparities, fulfilling ethical obligations, and ensuring that the promise of radiotheranostics translates into tangible benefits for all patients, regardless of economic context.[81-83]

The IAEA plays a pivotal role in supporting Member States in addressing the multifaceted challenges associated with advocacy in this arena. Through a comprehensive, multidisciplinary approach, the IAEA facilitates collaboration among Member States to tackle issues related to production, transportation, waste management, radiation protection, clinical applications, and regulatory perspectives of TRT.[84] By providing guidance, technical assistance, and capacity-building initiatives, the IAEA empowers Member States to enhance their capabilities in the safe and effective utilization of TRT, thereby improving healthcare outcomes for populations worldwide. The IAEA's commitment—also shared by Non-state Actors such as the WFNMB—to fostering international cooperation and knowledge sharing underscores its critical role in advancing the field of nuclear medicine and radiotheranostics and ensuring equitable access to this precision treatment globally.[61,84,85]

The recent adoption of the World Health Assembly Resolution on "Strengthening Medical Imaging Capacity" (WHA78.13) underscores the pivotal role of advanced imaging modalities, explicitly including theranostics, in enhancing patient outcomes.[5] Notably, the Resolution recognizes that effective implementation of radiotheranostics in LMICs depends on equitable access to high-quality imaging infrastructure. This international policy momentum provides an essential framework for integrating theranostics into global health strategies, supporting scalable, context-sensitive approaches for cancer care and noncommunicable diseases. Aligning national implementation efforts with WHO recommendations can accelerate the adoption of theranostics and narrow global disparities in patient access and outcomes.[5]

Conclusion

Radiotheranostics marks a transformative advance in precision oncology, promising significantly improved patient outcomes through individualized treatment approaches, yet its full potential, particularly in LMICs where cancer rates are climbing, hinges on the development of strategic, inclusive, and sustainable frameworks for implementation. This comprehensive review underscores that integrating radiotheranostics is not merely a matter of scientific progress or technical capability, but rather a complex systemic challenge requiring harmonized efforts spanning regulatory reforms, reliable radiopharmaceutical production, workforce education and training, sustainable financing, infrastructure development, and global research collaboration. Achieving success in this field demands the establishment of clear regulatory pathways, dependable supply chains, accessible and ongoing training, viable reimbursement models, and the active participation of LMICs in both clinical practice and research networks. Ensuring equitable access to radiotheranostics is a pressing global need, necessitating its incorporation into national cancer control strategies and health financing policies, all underpinned by persistent advocacy and support from international organizations such as the IAEA, WHO, and relevant professional societies, who play pivotal roles in technical assistance, capacity-building, and research support. Ultimately, radiotheranostics should not be confined to well-resourced settings but must be championed as a global public good, and with coordinated, multidisciplinary, and equity-focused efforts, it can become a foundational element of modern cancer care, delivering precise and transformative therapies to patients everywhere.

Declaration of competing interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Editor of the Seminars in Nuclear Medicine. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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References

1. Bodei L, Herrmann K, Schöder H, et al: Radiotheranostics in oncology: current challenges and emerging opportunities. Nat Rev Clin Oncol 19 (8):534-550, 2022. https://doi.org/10.1038/s41571-022-00652-y
2. Al-Ibraheem A, Scott AM, Abdlkadir AS, et al: Consensus nomenclature for radionuclide therapy: initial recommendations from nuclear medicine global initiative. J Nucl Med 66(5):757-763, 2025. https://doi.org/10.2967/jnumed.124.269215
3. Herrmann K, Schwaiger M, Lewis JS, et al: Radiotheranostics: a roadmap for future development. Lancet Oncol 21(3):e146-e156, 2020. https://doi.org/10.1016/S1470-2045(19)30821-6
4. Al-Ibraheem A, Zimmermann R, Abdlkadir AS, et al: Radiotheranostics global market and future developments. Semin Nucl Med 54(4):622-633, 2024. https://doi.org/10.1053/j.semnuclmed.2024.02.003
5. World Health Organization, Strengthening medical imaging capacity. The seventy-eighth World Health Assembly. WHA78.13. 2025. Accessed July 26, 2025. https://apps.who.int/gb/ebwha/pdf_files/WHA78/A78_R13-en.pdf
6. Trapani D, Garcia PJ, Schroeder L, et al: WHO model list of essential in vitro diagnostics: strengthening diagnostics capacity to transform health care for all. Lancet Global Health 12(3):e364-e365, 2024. https://doi.org/10.1016/S2214-109X(23)00568-5
7. Al-Ibraheem A: Theranostics in developing countries: addressing challenges and potentials from training to practice. World J Nucl Med 22 (03):171-173, 2023. https://doi.org/10.1055/s-0043-1774733
8. Jadvar H, Chen X, Cai W, et al: Radiotheranostics in cancer diagnosis and management. Radiology 286(2):388-400, 2018. https://doi.org/10.1148/radiol.2017170346
9. Hricak H, Mayerhoefer ME, Herrmann K, et al: Advances and challenges in precision imaging. Lancet Oncol 26(1):e34-e45, 2025. https://doi.org/10.1016/S1470-2045(24)00395-4
10. Brink A, Cerci JJ, Giammarile F, et al: Global challenges in the provision of theranostic services the International Atomic Energy Agency (IAEA) perspective. World J Nucl Med 2025. https://doi.org/10.1055/s-0045-1807251
11. Avila-Rodriguez MA, Jalilian AR, Korde A, et al: Current status on cyclotron facilities and related infrastructure supporting PET applications in Latin America and the Caribbean. EJNMMI Radiopharm Chem 7(1):14, 2022. https://doi.org/10.1186/s41181-022-00166-z
12. Abdel-Wahab M, Giammarile F, Carrara M, et al: Radiotherapy and theranostics: a Lancet Oncology Commission. Lancet Oncol 25(11): e545-e580, 2024. https://doi.org/10.1016/S1470-2045(24)00407-8
13. Kahlem P, Berenger-Molins P, Akbulut H: Theranostics-enabling high-tech centers: the value of centralizing resources in countries in development. F1000Research 13:283, 2024
14. Svenson S: Theranostics: are we there yet? Mol Pharm 10(3):848-856, 2013. https://doi.org/10.1021/mp300644n
15. Lapi SE, Scott PJH, Scott AM, et al: Recent advances and impending challenges for the radiopharmaceutical sciences in oncology. Lancet Oncol 25(6):e236-e249, 2024. https://doi.org/10.1016/S1470-2045(24)00030-5
16. Qaim SM: The present and future of medical radionuclide production. Radiochim Acta 100(8-9):635-651, 2012
17. Vogel W, Van der Marck S, Versleijen M: Challenges and future options for the production of lutetium-177. Eur J Nucl Med Mol Imaging 48 (8):2329-2335, 2021
18. Paans AM: Compact cyclotrons for the production of tracers and radiopharmaceuticals. Nukleonika 48(2):S169-S172, 2003

19. Slomka PJ, Miller RJH, Hu L-H, et al: Novel techniques: solid-state detectors, dose reduction (SPECT/CT). In: Nekolla SG, Rischpler C (eds): Hybrid Cardiac Imaging, Princeton, New Jersey, USA: Springer International Publishing, 103-129, 2022
20. Currie GM, Hawk KE, Rohren EM: Challenges confronting sustainability in nuclear medicine practice. Radiography 30:1-8, 2024. https://doi.org/10.1016/j.radi.2024.04.026
21. Bailey E, Bissolotti M, Camoni L: Nuclear medicine department: organization, staffing, and workflow optimization. In: Camoni L, Mansi L (eds): Nuclear Medicine Hybrid Imaging for Radiographers & Technologists, Princeton, New Jersey, USA: Springer Nature Switzerland, 249-263, 2025
22. Scott AM, Zeglis BM, Lapi SE, et al: Correction to Lancet Oncol 2024; 25: e250−59. Lancet Oncol 25(8):e336, 2024.. https://doi.org/10.1016/S1470-2045(24)00378-4
23. Scott AM, Zeglis BM, Lapi SE, et al: Trends in nuclear medicine and the radiopharmaceutical sciences in oncology: workforce challenges and training in the age of theranostics. Lancet Oncol 25(6):e250-e259, 2024. https://doi.org/10.1016/S1470-2045(24)00037-8
24. Cutler CS, Bailey E, Kumar V, et al: Global issues of radiopharmaceutical access and availability: a nuclear medicine global initiative project. J Nucl Med 62(3):422-430, 2021. https://doi.org/10.2967/jnumed.120.247197
25. Giammarile F, Paez D, Zimmermann R, et al: Production and regulatory issues for theranostics. Lancet Oncol 25(6):e260-e269, 2024. https://doi.org/10.1016/S1470-2045(24)00041-X
26. Mikhail-Lette M, Cordero L, Lievens Y, et al: Six country vignettes: strengthening radiotherapy and theranostics. J Cancer Policy 40: 100471. https://doi.org/10.1016/j.jcpo.2024.100471, 2024
27. Al-Ibraheem A, Abdlkadir A, Albalooshi B, et al: Theranostics in the Arab world; achievements & challenges. Jordan Med J 56(2), 2022
28. Al-Ibraheem A, Abdlkadir AS, Mohamedkhair A, et al: Cancer diagnosis in areas of conflict. Front Oncol 12:1087476. https://doi.org/10.3389/fonc.2022.1087476, 2022
29. Turner JH: Recent advances in theranostics and challenges for the future. Br J Radiol 91(1091). https://doi.org/10.1259/bjr.20170893, 2018
30. Radiopharmacy E: on radiopharmacy and radiopharmaceuticals. Bioconjug Chem 32(4):755-762, 2021
31. McDonald A: Nuclear power global status. IAEA Bull 49(2):45, 2008
32. Hricak H, Abdel-Wahab M, Atun R, et al: Medical imaging and nuclear medicine: a Lancet Oncology Commission. Lancet Oncol 22(4):e136-e172, 2021. https://doi.org/10.1016/S1470-2045(20)30751-8
33. Stokkel MPM, Gotthardt M, Herrmann K, et al: Theranostics in perspective: white paper. J Nucl Med 66(7):1007-1011, 2025. https://doi.org/10.2967/jnumed.125.269776
34. Mc Gillivray H, Uribe C, Rahmim A, et al: From diagnostics to theranostics, and why better cancer care will always be costly. BCMJ 62(10):373-376, 2020. 379 Premise
35. Ward ZJ, Scott AM, Hricak H, et al: Global costs, health benefits, and economic benefits of scaling up treatment and imaging modalities for survival of 11 cancers: a simulation-based analysis. Lancet Oncol 22 (3):341-350, 2021. https://doi.org/10.1016/S1470-2045(20)30750-6
36. Czernin J, Sonni I, Razmaria A, et al: The future of nuclear medicine as an independent specialty. J Nucl Med 60(suppl 2):3S-12S, 2019. https://doi.org/10.2967/jnumed.118.220558
37. Gonzalez S, Comte F, Israël JM, et al: Patient communication of nuclear imaging results: do nuclear medicine practitioners have a role to play? Eur J Nucl Med Mol Imaging 51(9):2528-2531, 2024. https://doi.org/10.1007/s00259-024-06768-w
38. Pascual TNB, Paez D, Iagaru A, et al: Guiding principles on the education and practice of theranostics. Eur J Nucl Med Mol Imaging 51 (8):2320-2331, 2024. https://doi.org/10.1007/s00259-024-06657-2
39. Faivre-Chauvet A, Bourdeau C, Bourgeois M: Radiopharmaceutical good practices: regulation between hospital and industry. Policy Brief. Front Nucl Med 2:2022, 2022. https://doi.org/10.3389/fnume.2022.990330
40. Radzina M, Saule L, Mamis E, et al: Novel radionuclides: demand, production and distribution for translational research in Europe. EJNMMI Radiopharm Chem 9(1):85, 2024. https://doi.org/10.1186/s41181-024-00318-3
41. Veit-Haibach P, Herrmann K, Zimmermann R, et al: Green nuclear medicine and radiotheranostics. J Nucl Med 66(3):340-343, 2025. https://doi.org/10.2967/jnumed.124.268928
42. Agency IAE: Regulations for the Safe Transport of Radioactive Material. Vienna, Austria: International Atomic Energy Agency, 2009
43. Kaushik D, Jangra P, Verma R, et al: Radiopharmaceuticals: an insight into the latest advances in medical uses and regulatory perspectives. J Biosci 46(1):27, 2021. https://doi.org/10.1007/s12038-021-00147-5
44. Le D: An overview of the regulations of radiopharmaceuticals. In: Wong FCL (ed): Locoregional Radionuclide Cancer Therapy: Clinical and Scientific Aspects, Princeton, New Jersey, USA: Springer International Publishing, 225-247, 2021
45. Perini EA, Skopchenko M, Hong TT, et al: Pre-feasibility study for establishing radioisotope and radiopharmaceutical production facilities in developing countries. Curr Radiopharm 12(3):187-200, 2019
46. Ostuni E, Taylor MRG: Commercial and business aspects of alpha radioligand therapeutics. Front Med 9:1070497. https://doi.org/10.3389/fmed.2022.1070497, 2023
47. Martins S, Jesus Â, Suárez AM: Pharmacovigilance of radiopharmaceuticals: challenges and opportunities. J Pharm Technol 40(5):257-259, 2024. https://doi.org/10.1177/87551225241266172
48. Brosa M, García del Muro X, Mora J, et al: Orphan drugs revisited: cost−effectiveness analysis of the addition of mifamurtide to the conventional treatment of osteosarcoma. Expert Rev Pharmacoecon Outcomes Res 15(2):331-340, 2015. https://doi.org/10.1586/14737167.2015.972378
49. Andronis L, Goranitis I, Bayliss S, et al: Cost-effectiveness of treatments for the management of bone metastases: a systematic literature review. Pharmacoeconomics 36(3):301-322, 2018. https://doi.org/10.1007/s40273-017-0595-0
50. White BE, Mujica-Mota R, Snowsill T, et al: Evaluating cost-effectiveness in the management of neuroendocrine neoplasms. Rev Endocr Metab Disord 22(3):647-663, 2021. https://doi.org/10.1007/s11154-020-09608-y
51. Giammarile F, Knoll P, Kunikowska J, et al: Guardians of precision: advancing radiation protection, safety, and quality systems in nuclear medicine. Eur J Nucl Med Mol Imaging 51(6):1498-1505, 2024. https://doi.org/10.1007/s00259-024-06633-w
52. Suji T, Sullivan R, Bowsher G: Radiology in conflict: scoping review. Confl Health 18(1):8, 2024. https://doi.org/10.1186/s13031-023-00550-9
53. Al-Ibraheem A, Abdlkadir AS, Albalooshi B, et al: Current status of theranostics in West Asia: a country-based surveillance study. Nucl Med Mol Imaging (2010) 2025. https://doi.org/10.1007/s13139-025-00914-4
54. Warner S: Diagnostics+ therapy= theranostics: strategy requires teamwork, partnering, and tricky regulatory maneuvering. The Scientist 18 (16):38-40, 2004
55. Bautista-Peñalosa P: Real challenges before, during, and after establishing a theranostics center in developing countries. Nucl Med Mol Imaging (2010) 2025. https://doi.org/10.1007/s13139-025-00918-0
56. Herrmann K, Giovanella L, Santos A, et al: Joint EANM, SNMMI, and IAEA Enabling guide: how to set up a theranostics center. J Nucl Med 63(12):1836-1843, 2022. https://doi.org/10.2967/jnumed.122.264321
57. Edam AN, Sulieman A, Sam AK, et al: Quality control of radiopharmaceuticals and diagnostic nuclear medicine equipment. Radiat Phys Chem 167:108247. https://doi.org/10.1016/j.radphyschem.2019.03.051, 2020
58. Saha GB: Quality control of radiopharmaceuticals. Fundamentals of Nuclear Pharmacy. New York: Springer, 143-167, 1992
59. Gillings N, Hjelstuen O, Behe M, et al: EANM guideline on quality risk management for radiopharmaceuticals. Eur J Nucl Med Mol Imaging 49 (10):3353-3364, 2022. https://doi.org/10.1007/s00259-022-05738-4
60. Pascual TNB, Dondi M, Paez D, et al: IAEA programs in empowering the nuclear medicine profession through online educational resources. Semin Nucl Med 43(3):161-166, 2013. https://doi.org/10.1053/j.semnuclmed.2012.11.005
61. Frangos S: New horizons for the World Federation of Nuclear Medicine and Biology: achievements, partnerships, and future directions. Eur J

Nucl Med Mol Imaging 52(2):376-379, 2025. https://doi.org/10.1007/s00259-024-06990-6
62. Muylle K, Maffioli L: Nuclear medicine training in Europe: “all for one, one for all”. J Nucl Med 58(12):1904-1905, 2017. https://doi.org/10.2967/jnumed.117.201012
63. Stokkel MPM, Owers EC: Hybrid training in nuclear medicine: where are we going to? Eur J Nucl Med Mol Imaging 50(8):2231-2235, 2023. https://doi.org/10.1007/s00259-023-06223-2
64. Grossi RM: The IAEA’s Rays of Hope leverages nuclear science and collaboration to fight cancer in developing countries. J Cancer Policy 34:100357. https://doi.org/10.1016/j.jcpo.2022.100357, 2022
65. Grossi RM: Rays of hope: the IAEA ups its commitment to cancer care. Lancet Oncol 23(6):702-703, 2022. https://doi.org/10.1016/S1470-2045(22)00138-3
66. Dondi M, Torres L, Marengo M, et al: Comprehensive auditing in nuclear medicine through the International Atomic Energy Agency Quality Management Audits in Nuclear Medicine (QUANUM) Program. Part 1: the QUANUM Program and Methodology. Semin Nucl Med 47 (6):680-686, 2017. https://doi.org/10.1053/j.semnuclmed.2017.07.003
67. Dondi M, Kashyap R, Pascual T, et al: Quality management in nuclear medicine for better patient care: the IAEA program. Semin Nucl Med 43 (3):167-171, 2013. https://doi.org/10.1053/j.semnuclmed.2012.11.006
68. Paez D, Marengo M, Bomanji J, et al: Quality improvement initiative of the IAEA in nuclear medicine: a tool to assess staffing needs within the QUANUM framework. Nucl Med Commun 43(9):967-969, 2022. https://doi.org/10.1097/mnm.0000000000001584
69. Abdel-Wahab M, Coleman CN, Eriksen JG, et al: Addressing challenges in low-income and middle-income countries through novel radiotherapy research opportunities. Lancet Oncol 25(6):e270-e280, 2024. https://doi.org/10.1016/S1470-2045(24)00038-X
70. Strosberg J, El-Haddad G, Wolin E, et al: Phase 3 trial of ^{177}Lu-Dotatate for midgut neuroendocrine tumors. N Engl J Med 376(2):125-135, 2017. https://doi.org/10.1056/NEJMoa1607427
71. Sartor O, de Bono J, Chi KN, et al: Lutetium-177−PSMA-617 for metastatic castration-resistant prostate cancer. N Engl J Med 385(12):1091-1103, 2021. https://doi.org/10.1056/NEJMoa2107322
72. Parker C, Nilsson S, Heinrich D, et al: Alpha emitter radium-223 and survival in metastatic prostate cancer. N Engl J Med 369(3):213-223, 2013. https://doi.org/10.1056/NEJMoa1213755
73. Al-Ibraheem A, Abdlkadir AS, Sweedat DA, et al: From despair to hope: first Arabic experience of 177Lu-PSMA and 161Tb-PSMA therapy for metastatic castration-resistant prostate cancer. Cancers (Basel) 16 (11):1974, 2024
74. Urbain JL, Scott AM, Lee ST, et al: Theranostic Radiopharmaceuticals: a universal challenging educational paradigm in nuclear medicine. J Nucl Med 64(6):986-991, 2023. https://doi.org/10.2967/jnumed.123.265603
75. Cerci JJ, Fanti S, Lobato EE, et al: Diagnostic performance and clinical impact of ^{68}Ga-PSMA-11 PET/CT imaging in early relapsed prostate cancer after radical therapy: a prospective multicenter study (IAEA-PSMA Study). J Nucl Med 63(2):240-247, 2022. https://doi.org/10.2967/jnumed.120.261886
76. Brabander T: How to design a theranostic trial? Endocrine 4:e230045, 2024
77. Wang SJ: Recent advances in clinical trial design considerations in Thera“nostics”. Contemp Clin Trials 96:106100. https://doi.org/10.1016/j.cct.2020.106100, 2020
78. Youngblood SN: Bullying in the nuclear medicine department and during clinical Nuclear medicine education. J Nucl Med Technol 49 (2):156-163, 2021. https://doi.org/10.2967/jnmt.120.257204
79. Momodu JI, Carvajal C, Pryma DA, et al: The Lancet Oncology Commission: radiotherapy & theranostic services in LMICs: minding & mending the gaps. Int J Radiat Oncol Biol Phys 120(4):931-935, 2024. https://doi.org/10.1016/j.ijrobp.2024.09.013
80. Jalilian A, Korde A, Starovoitova V, et al: Radioisotope products and the medicine of the future: an IAEA perspective. Regul Res Med Eval 12 (4):364-378, 2022
81. Blythe JA, Ng TSC: Ethical principles for practice building in the era of targeted radioligand therapy. Clin Imaging 116:110334. https://doi.org/10.1016/j.clinimag.2024.110334, 2024
82. Strigari L, Schwarz J, Bradshaw T, et al: Computational nuclear oncology toward precision radiopharmaceutical therapies: ethical, regulatory, and socioeconomic dimensions of theranostic digital twins. J Nucl Med 66(5):748-756, 2025. https://doi.org/10.2967/jnumed.124.268186
83. Bekker L-G, Alleyne G, Baral S, et al: Advancing global health and strengthening the HIV response in the era of the Sustainable Development Goals: the International AIDS Society—Lancet Commission. The Lancet 392(10144):312-358, 2018. https://doi.org/10.1016/S0140-6736(18)31070-5
84. Jalilian AR, Kleynhans J, Bouziotis P, et al: IAEA activities to support the member states in the production of targeted alpha therapy radiopharmaceuticals. Nucl Med Biol 144-145:109008. https://doi.org/10.1016/j.nucmedbio.2025.109008, 2025
85. Jalilian AR, Ocampo-García B, Pasanphan W, et al: IAEA contribution to nanosized targeted radiopharmaceuticals for drug delivery. Pharmaceutics 14(5):1060, 2022