Six Country Vignettes: Strengthening Radiotherapy and Theranostics

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Abstract

Background: For cancer patient populations worldwide, the synchronous scale-up of diagnostics and treatments yields meaningful gains in survival and quality of life. Among advanced cancer therapies, radiotherapy (RT) and theranostics are key to achieving practical, high-quality, and personalized precision medicine - targeting disease manifestations of individual patients and broad populations, alike. Aiming to learn from one another across different world regions, the six country vignettes presented here depict both challenges and victories in *de novo* establishment or improvement of RT and theranostics infrastructure.

Methods: The International Atomic Energy Agency (IAEA) convened global RT and theranostics experts from diverse world regions and contexts to identify relevant challenges and report progress in their own six countries: Belgium, Brazil, Costa Rica, Jordan, Mongolia, and South Africa. These accounts are collated, compared, and contrasted herein.

Results: Common challenges persist which could be more strategically assessed and addressed. A quantifiable discrepancy entails personnel. The estimated radiation oncologists (ROs), nuclear medicine physicians (NMPs), and medical physicists (MPs for RT and nuclear medicine) per million inhabitants in the six collective countries respectively range between 2.69–38.00 ROs, 1.00–26.00 NMPs, and 0.30–3.45 MPs (Table 1), reflecting country-to-country inequities which largely match World Bank country-income stratifications.

Conclusion: Established goals for RT and nuclear medicine advancement worldwide have proven elusive. The pace of progress could be hastened by enhanced approaches such as more sustainably phased implementation; better

multinational networking to share lessons learned; routine quality and safety audits; as well as capacity building employing innovative, resource-sparing, cutting-edge technologic approaches.

Bodies such as ministries of health, professional societies, and the IAEA shall serve critical roles in convening and coordinating more innovative RT and theranostics translational research, including expanding nuanced global database metrics to inform, reach, and potentiate milestones most meaningfully.

Policy Summary: Aligned with WHO 25x25 NCDs target; WHA70.12 and WHA76.5 resolutions.

Keywords: Theranostics; Radiotherapy; Nuclear medicine; Brachytherapy; Global health; Public health; Low-middle-income countries

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Introduction

Cancer causes nearly one in six deaths globally [1]. Increasing cancer rates in low-and-middle-income countries (LMICs) particularly stress healthcare systems. Of almost 10 million cancer-related deaths worldwide in 2020, 70% occurred in LMICs, especially those below age 65 [2]. Even with diagnoses made, insufficient downstream treatment resources represent the current reality for many, recognizing that cancer care capacity is multimodal: systemic therapy, surgery, radiation therapy, theranostics, image-guided interventional radiology procedures such as tumour ablations, and more [3].

Following evidence-based guidelines to achieve the best patient outcomes, more than half of adult cancer patients and more than one-third of paediatric cancer patients need radiotherapy (RT), from curative treatment to palliation. However, over half of this target population resides in LMICs where RT is unavailable. In low-income countries (LICs), more than nine of ten cancer patients currently lack RT access [4], [5].

Complementary to the medical use of ionizing radiation for RT is the emerging field of radiopharmaceutical therapy, whereby combining imaging and therapy of selected cancer targets with radiopharmaceuticals is possible; a precision medicine approach to treating cancer, including advanced and metastatic neoplasms. Though approved theranostics currently apply to a handful of malignancies (especially thyroid, prostate, and neuroendocrine tumours) the number of promising radiopharmacologic agents is expanding rapidly. Acknowledging that positron emission tomography (PET) is key to the diagnostic aspect of theranostics and to high-quality cancer imaging in general, the IAEA estimates a ratio of 286,000 inhabitants per PET scanner in high-income countries (HICs) compared to 250 million inhabitants per PET unit in LICs [6].

Such stark socioeconomic stratifications run countercurrent to ethics and clinical oncology guidelines intended for all, wherein the roles of both RT and medical imaging, including nuclear medicine and theranostics, are fundamental quality metrics [7].

To illustrate diversity in implementation stages of RT and theranostics infrastructure, serially presented here are expert testimonials thoughtfully selected from: Belgium, Brazil, Costa Rica, Jordan, Mongolia, and South Africa.

Country Vignettes

Belgium

Infrastructure availability/distribution

Belgian data on RT equipment, personnel, activities, and outcome data are readily available through the Belgian College for Physicians of Radiation Oncology Centres [8]. Some such data contribute to the worldwide IAEA-DIRAC (Directory of Radiotherapy Centres) showing that Belgium has more RT units per population than the European average [8]. In 2014, Belgium had 8.24 LINACs per million inhabitants compared to Europe's 5.5 [9]. In 2021, 88 external beam radiotherapy (EBRT) machines were reported, with suitable brachytherapy and intra-operative radiotherapy availability countrywide [10]. Belgium also excels in intensity-modulated (IMRT) and image-guided radiotherapy (IGRT)-capable machines, with 100% of equipment capable of these compared to respective European medians of 73% and 45% [9].

An average three Belgian hospitals provide RT per million inhabitants compared to 1.8 across Europe [10]. Twenty-four primary centres operate 11 satellites, translating into 3.7 EBRT devices per primary department but only 2.5 per RT site [10].

The Belgian nuclear medicine landscape is akin to RT, well-equipped with 155 SPECT/CTs and 33 PET/CTs (in 24 PET-centres), respectively 13.4 and 2.8 units per million inhabitants (2022) [11].

Staffing

According to an IAEA-led survey, in 2023 Belgium had 300 nuclear medicine physicians (NMPs) for an approximate 11.6 million population, or 26 NMPs per million inhabitants (Fig. 4) [12].

Conventional nuclear medicine such as SPECT/CT is well-distributed geographically, unlike PET/CT where uneven distribution favors Brussels due to the concentration of university hospitals in and around the capital, each entitled to two PET/CTs [13]. Seven years post-publication of the Royal Decree, criteria to enable PET/CT growth are revised to meet dynamic population-based needs for which evidence shows added value.

Historically, Belgium has helped pioneer nuclear medicine, among first countries to install PET in the 1980s. Belgian researchers showcased PET's worth for lung cancer and lymphoma. Today, Belgium ranks among medical radioisotope production leaders, including for therapeutic ones like Lutetium-177.

Barriers to utilization

The radiopharmaceutical industry footprint, the cost of necessary equipment, qualified personnel for in-house labelling of therapeutic tracers, and regulations limit the number of centres that produce therapeutic agents. Currently, five centres have obtained reimbursement by Belgian social insurance for ^{177}Lu-DOTATATE and/or ^{177}Lu-PSMA (first reimbursement in June 2021) on a limited scale. Although the distribution network is enlarged through interhospital collaboration agreements, and in-house labelling provides earlier access to new theranostics, needs surpass production capacity. Since August 2022, reimbursement is granted for commercially available ^{177}Lu-DOTATATE in Belgium, providing equitable access to radionuclide therapy (RNT) for patients with neuro-endocrine tumours. The introduction of commercially available ^{177}Lu-PSMA is expected to optimize RNT access for prostate cancer, given the recent application for its reimbursement in Belgium.

Challenges remain in enabling equitable access to innovative RT and theranostics. Belgium shows the highest evidence-based need for RT across Europe, where more than 53% of all cancer patients require RT at least once during their disease but only 39% benefit [14], [15]. Provider and health service-related aspects – including awareness, organization, and economics – influence access and utilization [14]. While hospital budgets partially cover investment in new RT equipment, co-financing with reimbursement fees to cover professional activities is necessary. Furthermore, the reimbursement system developed two decades ago lags evolving evidence. For example, swift deployment of hypofractionated RT is hindered by reimbursement mechanisms based primarily upon the number of fractions [16].

Thus, innovation makes slow inroads into practice, impelled more so by efforts of professional healthcare providers than by structured national planning. For example, one clinical proton-beam room is operational, and two MR-LINACs were recently installed.

Another example, despite growing internationally available clinical efficacy evidence for stereotactic body radiotherapy (SBRT), reimbursement was not granted in 2011 due to a lack of Belgian data at the time.

To foster RT innovation adoption, Belgium needed alternative financing models. 2013 launched the "coverage with evidence development" (CED) project for innovative RT. With collaboration of the Belgian Cancer Registry, the Belgian Institute for Health and Disability Insurance, and the Belgian Radiation Oncology Community, this project registered more than 6,000 SBRT treatments between 2013 – 2019, and patient outcome analysis led to SBRT's inclusion in the Belgian reimbursement system in 2020 [16].

Like other European countries, Belgium also grapples with shortages of medical imaging technologists and RTT staff, slowing the implementation of innovation.

In summary, while RT and nuclear medicine availability in Belgium compares well with European averages, access, utilization, and especially innovation fall short of the best possible 21st-century medical management of patients. National and regional levels require enhanced evidence-based planning. Prevailing strategies jeopardize investment in and replacement of equipment and impede rapid implementation of innovations in daily practice. Novel financing approaches such as CED could facilitate earlier access. Ongoing revisions of financing and reimbursement systems for specialist care stand to better align both RT and nuclear medicine practices with scientific and clinical progress.

Brazil

Infrastructure availability/distribution

Brazil covers 77% of its 214 million inhabitants under public healthcare, the "*Sistema Único de Saúde* (SUS)". Average SUS reimbursement in 2021 was US$843 per patient, a significant challenge to advanced RT implementation. Brazilian RT departments are concentrated in the most developed regions, the Southeast and South, as well as state capitals. A veritable subcontinent, Brazil has vast geographic diversity where a public patient travels an average 76km-distance to receive RT and patients from the North travel, in some cases, more than 1600km. Granted insufficient RT access, in 2012 the government started a project to procure 100 LINACS. In April 2022, only 48 such units remained clinically operational, a problem compounded after a decade by machine obsolescence [17]. Despite broader spectrum availability of technologies in private medical institutions, some national reimbursement coding policies make it difficult for patients to access contemporary RT. Only head and neck cancer, and more recently thoracic malignancies, formally require IMRT treatments. Nevertheless, considerable investment into high-tech cancer treatment machines recently took place in some Brazilian hospitals, including by big oncology companies.

Staffing

As of December 2019, 646 radiation oncologists (Fig. 3) were engaged in patient care alongside 737 physicists (Fig. 5). These specialists were distributed in 263 RT departments of different medical institutions, working with 409 LINACs and 10 Cobalt units, the latter used primarily for palliation. 77% of the LINACS have Multi-Leaf Collimators (MLCs), 42% digital portal devices, 20% Cone Beam Computed Tomography (CBCT), and 9% robotic tables. About a quarter of these machines are over 15 years old. Available RT technologies include IMRT at 51%, VMAT at 33%, radiosurgery at 38%, and SBRT at 30% [18].

In 2012, with the 100 LINACS Project, hospitals were incentivized financially to open residency programs. Unfortunately, most lacked proper faculty and training infrastructure. Among latest technologies available locally (including IMRT, VMAT, IGRT, Radiosurgery, and SBRT), only 32.4% of the programs had access to all and

29.7% to none. These differences manifested themselves in the board exams where, in recent years, only 32% of applicants succeeded.

The Brazilian Radiotherapy Society has shared results of sustainability studies with the Ministry of Health. One hindrance to RT development is underfinancing. Using accurate, actual, value-added economic numbers could better shape strategic decisions to overcome challenges.

Complementary to RT, nuclear medicine in Brazil encompasses 25 centres for training NMPs. In 2020, there were 1,020 NMPs in Brazil for an approximate national population of 211 million, fewer than two NMPs per million inhabitants. The National Nuclear Energy Commission of Brazil is authorized to license NMPs for diagnosis and therapy, all registered with the Brazilian Medical Association and the Brazilian Nuclear Medicine Society which controls board certification. Concurrently, there are 57 nuclear medicine medical physicists in Brazil. These numbers spotlight current limits in access to radiopharmacy and medical physics education. For nuclear medicine technologists, training is more readily available.

Theranostics procedures available include radioiodine for thyroid diseases, ^{131}I-MIBG and ^{177}Lu-DOTATATE for neuroendocrine tumours (NETs), and ^{177}Lu-PSMA for prostate cancer. Regarding nuclear medicine dosimetry, in Brazil advances occur slowly – fixed doses without dosimetry calculation are commonplace in daily practice.

Barriers to utilization
Challenges persist in incorporating nuclear medicine procedures in Brazil, such as access, regulation, and reimbursement. Insufficiencies in equipment and therapeutic rooms translate into limited availability. To break the cycle of low investment and limited access, more funding is needed.

Additionally, approvals of new radiotracers by the National Health Surveillance Agency are time-consuming. Over the past 10 years, obstacles in approvals and excessive costs have slowed the introduction of new tracers into the Brazilian market. Rules for requesting registration were modified in 2020, expediting the introduction of emerging radiotracers. Simultaneous high costs for requesting and maintaining registrations have made several small-scale tracers disappear from the Brazilian market. For example, orphan drugs without major pharmaceutical companies interested in them encounter extreme difficulty in becoming viable and remaining so in Brazil's market.

Costa Rica

Infrastructure availability/distribution
Four Costa Rican centres have RT, two public (the Hospital Mexico and Juan de Dios) and two private. The public sector has eight LINACs and the private sector two. Significant steps towards local RT took place in 2010, sponsored by the IAEA. Specifically, IAEA financial support enabled Costa Rica to venture into techniques such as IMRT, VMAT, IGRT, SRS, and SBRT.

Regarding nuclear medicine, in 2020 the first local Cyclotron was installed by the Atomic, Nuclear, and Molecular Science Research Center (CICANUM) at the University of Costa Rica [19]. The only PET-CT in the country exists in a private facility.

MRIs are disproportionately more available in the private sector, but most patients lack the means to access private healthcare. Public MRI access is limited to two units in the Calderón Guardia Hospital of the public sector. Such discrepant care availability has entered public discourse.

Patients of local RT specialists have insufficient access to MRI and PET-CT exams. Limited diagnostic strategies impair the use of stereotactic radiotherapy (SRT). To improve RT, in 2008 Costa Rican Social Security developed a roadmap which included new equipment acquisition and efforts to improve both coverage of and accessibility to RT techniques. The project encountered delays, but two years ago new momentum rekindled the expansion of RT services in the public sector, though currently limited to urban settings.

While Costa Rica invested in RT equipment, synergistic IAEA sponsorship enabled local RT professionals to complete their education in Europe and America. Such academic exchanges empowered local professionals, improving their understanding of advanced RT, the safe application of ionizing therapies, and relevant diagnostics. Generous IAEA financial support has enabled Costa Rica to achieve some of the highest RT utilization rates in Central America.

Staffing

The national radiation medicine training landscape comprises eight medical schools, among postgraduate studies under the University of Costa Rica, including residencies in diagnostic radiology, nuclear medicine, and radiation oncology. Dosimetrists receive separate training. State and private universities offer comprehensive dosimetry training courses for specialists. As well, two medical physics academic master's programs exist in two public universities (Universidad de Costa Rica and Universidad National). The University of Costa Rica also opened a school of health technology with multidisciplinary RT training operating since the mid-2000s.

According to data collected through the worldwide IAEA Nuclear Medicine Staff Survey, in 2023 the number of NMPs in the country was six for a population of around 5.1 million, or approximately one NMP per million inhabitants (Fig. 4) [12]. The number of relevant MPs in the country is four (Fig. 5) [12].

Public and private health system branches possess different resources and treatment capacities. Currently, the private sector has two Radiation Oncology Centres, one with five LINACs, one surface therapy unit, and one brachytherapy unit. The private health sector also provides treatments with Cyberknife, Trilogy equipment, and LINACs for intraoperative RT. Currently available procedures include 3D radiotherapy, 2D brachytherapy, superficial therapy, intraoperative radiotherapy, intra- and extracranial SRT [20].

Barriers to utilization

However, these procedures are unequally accessible to the populace due to discrepant coverage – 8% of the Costa Rican population has private medical insurance. In comparison, around 98% of the public has access to national Social Security resources. The current coverage system causes tensions and presents challenges – for instance, given a national population of 5.1 million, the public sector does not have enough equipment for ERT. The Hospital Mexico RT has worked uninterruptedly Monday to Saturday 24/7 since 2018 (six LINACs), and the other public hospital with RT, Juan de Dios, has two LINACs.

The Ministry of Health sets local RT and nuclear medicine regulatory requirements, the only governing and regulatory body for licensing, operations, and handling radioactive waste. According to regulations implemented in 2018, Cobalt equipment is no longer used nationally. Only one facility, the Hospital Mexico, recently replaced their brachytherapy device, undertaking 2D- and CT-based brachytherapy in selected cases for the whole country with no waitlists. Brachytherapy equipment, having a half-life, is replaced every three months and is an ionizing source of, specifically, Iridium-192. Regarding theranostics, ^{131}I is available for thyroid cancer.

Jordan

Jordan, nearly 89,000 km^2, population 10.9 million, is an upper-middle income (UMI) country at the heart of the Middle East [21]. National cancer incidence has increased by 60% in the past decade, the second leading cause of mortality after cardiovascular diseases [22]. Better strategizing of high-quality cancer care in Jordan is needed to fully address this alarming trend [23].

Establishment of the King Hussein Cancer Center (KHCC) has transformed cancer diagnostic and therapeutic capacity in Jordan [24]. Since 2002, KHCC has been a leading regional provider of oncology services, including theranostics and RT.

Staffing

Historically, in 1964 Al-Basheer Hospital established the first RT service where, from 1987, physicians received specialty training, graduating in RT through an implemented program. In 2004, KHCC introduced a comprehensive four-year RT residency program with an international externship component. These initiatives have trained over 41 RT specialists (Fig. 2).

Similarly, three nuclear medicine residency programs have been established, accredited by the Jordan Medical Council. KHCC/Jordan University Hospital (combined program), the Ministry of Health, and the King Hussein Medical City house these programs. To date, many physicians can apply for the Jordanian Board, helping address staffing shortages in Jordan and neighboring countries. According to a worldwide IAEA Nuclear Medicine Staff Survey, Jordan has approximately three NMPs per million inhabitants (Fig. 4) [12].

Infrastructure availability/distribution
Jordan has 16 LINACs, two cyclotrons, 11 PET/CTs, 19 SPECTs, and three SPECT/CTs (Fig. 1). Inaugurated in December 2016, the Jordan Research and Training Reactor (JRTR) was the first nuclear reactor in Jordan and has contributed to production of ^{131}I and ^{99m}Tc [24]. Currently, JRTR provides ^{161}T and ^{166}Ho irradiation services to international radioisotope companies [25]. The next phase will include ^{177}Lu production. JRTR exemplifies nuclear technology's peaceful applications to address medical, patient care needs.

In theranostics, Jordan has significantly advanced. Radioiodine, for the diagnosis and treatment of thyroid cancer, was first implemented in 1981 [22]. The introduction of ^{18}F-FDG-PET/CT in 2004 and various radiopharmaceuticals have revolutionized cancer diagnosis and treatment [24]. KHCC has pioneered novel theranostics, including the use of ^{68}Ga DOTA-peptide PET/CT for NET in 2013 and ^{68}Ga PSMA PET/CT for high-risk prostate cancer in 2014 [4]. The same year saw the introduction of Peptide Receptor Radionuclide Therapy (PRRT) using ^{177}Lu-DOTATATE therapy for NET cases. More recently,^{177}Lu PSMA was implemented for metastatic castration-resistant prostate cancer [24].

Barriers to utilization
However, theranostics and advanced RT are confined to the capital, Amman. Radiopharmacy and dosimetry personnel shortages and limited access to specific therapeutic radiopharmaceuticals exist. The high cost and limited access to therapeutic radiopharmaceuticals, like ^{223}Ra and ^{90}Y, hinder their envisioned introduction [26]. The lack of advanced RT techniques, such as MRI LINAC, Cyberknife, and Tomotherapy, hinders optimal treatment for cancer patients. Moreover, price surges may impede progress, such as for ^{177}Lu-DOTATATE and ^{177}Lu-PSMA.

Regulatory bodies such as the Energy and Minerals Regulatory Commission and the Jordan Food and Drug Administration (JFDA) ensure the safety and regulation of nuclear medicine and radiation protection. However, improvement is needed to increase nuclear medicine dosimetry staff expertise available to services.

Cancer care coverage is free for all Jordanians at public hospitals, primarily Al-Basheer Hospital and the Royal Medical Services (RMS). KHCC provides free comprehensive diagnostic and therapeutic services to over 70% of Jordanian cancer patients after referral from the Royal Court or Ministry of Health [27].

Despite much progress in local cancer diagnostics and treatment, gaps persist. A strategic plan could appropriately expand relevant availability countrywide, prioritizing known barriers and shortages in staff, machines, and the geographical distribution of centres.

Mongolia

Infrastructure availability/distribution
Mongolia's oncological services had their genesis in 1959, with the pivotal establishment of the specialized Radiotherapy Hospital. Equipped with GUT-Co-60-400 and Luch-1 gamma therapy devices in 1961, the institution's technological capacity expanded with AGAT-C telecobalt, a ROKUS-M high-energy x-ray unit, and an AGAT-B brachytherapy following the 1982 hospital construction. These milestones laid groundwork for Mongolia's RT progress. In 1975, the First Central Hospital of Mongolia established the first nuclear medicine department, becoming the sole provider of SPECT/CT. With the introduction of Mongolia's first-ever PET/CT facility at the Second State Central Hospital in 2021, nuclear medicine has further developed.

Notably, the NCCM introduced linear accelerator-based 3D conformal RT in 2019, having treated over 3,000 patients. IAEA Regional Cooperative Agreement (RCA) RT courses trained local specialists to handle LINAC technologies. The introduction of CT-based 3D Image Guided Brachytherapy in 2018 and the country's first IMRT in 2022 marked transformative moments in Mongolia's RT.

International expertise has played a vital role, with IAEA contributions improving local radiation use, control, and protection practices. Collaborative efforts with the government and international partners have proven crucial to continued RT expansion. Planned installation of a high-precision LINAC at NCCM, approved by the Mongolian government in 2020, aims to introduce advanced techniques like SRS and SBRT. IAEA support shall prove essential for its safe implementation and relevant personnel training.

Mongolia's only RT facility, the NCCM, houses two LINACs, two teletherapy machines, and a brachytherapy unit with a Co-60 source. Despite these capabilities, advanced radiotherapy techniques like 4D-gating and SBRT have remained unavailable due to insufficiencies in specialized staff and advanced equipment. Since 2019, medical insurance has covered 3D conformal RT. Efforts are ongoing to establish tailored assessments by the insurance system to address treatment complexities.

Quality assurance (QA) programs ensure procedural safety and efficiency. International and national standards are adhered to by Major QA equipment. Mongolia's regulatory framework encompasses Nuclear Energy Law, Radiation Safety Standards, Radiation Safety Principles, and more. "Radiation Protection and Safety Protocol" of the NCCM, introduced in 2019, addresses waste management separately.

Staffing

After 2-year oncology residency, medical doctors take the NCCM's 6-month Radiation Oncology Training Program. Mongolia lacks dedicated schools for medical physicists, dosimetrists, and technicians in the radiotherapy field. However, in 2019, graduates in nuclear physics started to undertake a program that includes human anatomy, basic oncology, radiobiology, and imaging anatomy courses, primarily tailored to physicists and dosimetrists by NCCM, with the Health Sciences University of Mongolia's assistance. The IAEA's Technical Cooperation Projects and Regional Cooperative Agreements contributed significantly to Mongolia's radiotherapy service improvement through training syllabi, facilitated short-term training for modern radiotherapy technologies, and networking with experts from developed countries.

Mongolia has one SPECT/CT and two PET/CT machines across the country, with performance of 1,250 SPECT/CT and 1,500 PET/CT examinations yearly, accounting only for about 25 – 30% of the 4,991 late-stage newly diagnosed cancer cases. Meanwhile, the ^{131}I therapy is the only well-established therapy in Mongolia since 1992, while cancer incidence presents a high demand for different types of radiopharmaceutical therapies. To increase theranostic accessibility and improve the quality of life of cancer patients, expanding the types of diagnostics and therapies available would be optimal.

Barriers to utilization

In conclusion, Mongolia's radiation therapy landscape lacks enough specialized training institutions, relying on the NCCM's Radiation Oncologist Training Program for education. Despite the NCCM's equipped facilities, challenges persist in introducing advanced techniques due to equipment deficiencies and staff training gaps. Ongoing efforts aim to bridge these gaps, ensuring safer and more efficient radiotherapy practices while complying with regulatory requirements.

Mongolia's RT and nuclear medicine journey has witnessed significant progress, fueled by the gradual introduction of advanced technologies, international collaboration, and training initiatives. Continued efforts and partnerships will be fundamental to further expanding Mongolia's radiation medicine, ultimately improving population-based patient outcomes and quality of life.

South Africa

Infrastructure availability/distribution

RT in South Africa includes 88 state-of-the-art LINACs. One South African strength is established training that serves the continent. Around 354 registered radiation oncology-focused professionals in the Health Professions Council of South Africa (HPCSA) provide quality, cost-effective care. Around 27% of the 354 total experts work in state facilities. The country also boasts successful QA programs and impactful oncology congresses. Addressing common cancers in the region (such as prostate, breast, and cervical) is prioritized.

Access has improved in South Africa, with 86.4% of referred postmastectomy patients and 78.6% of breast-conserving surgery patients completing adjuvant RT because of proximity [28]. The survival rate is 50% in all breast cancer stages [29]. Advancement includes offering TARGIT-IORT TARGIT–intraoperative radiation therapy (IORT), which may offer a viable alternative to improve treatment efficiency and alleviate hospital patient loads [30].

The five-year overall survival for patients with cervical carcinoma is 71.95% in stage IIB and 49.7% in stage IIIB [31]. The Pretoria General Hospital, renamed the Steve Biko Academic Hospital, has historically been a leading theranostics institution in South Africa, pivotal in national nuclear medicine development. The hospital provides essential therapeutic radiopharmaceuticals such as PSMA Radioligand Therapy (PRLT) for Prostate Cancer with Lu-177 PSMA, PRRT for NETs, Lu-177 Zolidronate for bone pain palliation, and more. It also established local guidelines for procedures like PRRT [32] and PRLT [33]. While several university hospitals stand out, many lack theranostics, therefore limiting training opportunities and patient access. South Africa is considered amongst global leaders regarding targeted alpha therapy for prostate cancer [34]. IAEA funding has facilitated educational collaboration and supported institutions like NECSA/NTP and iThemba Labs, global radiopharmaceuticals suppliers.

Governmental institutions like the National Department of Science and Innovation have also contributed to South Africa's nuclear medicine, funding initiatives like the Nuclear Medicine Research Infrastructure (NuMeRI). This platform advances precision medicine capabilities, aligned with national health goals.

Staffing

The nuclear medicine landscape encompasses seven academic institutions offering postgraduate training in medical physics, radiobiology, radiation protection, and more. IAEA data from 2023 indicates 120 NMPs for an estimated population of 60 million, or two NMPs per million inhabitants (Fig. 4) [12]. Diagnostic and therapeutic radiopharmaceuticals are strong in S. Africa. There are 59 active nuclear medicine facilities in S. Africa: 46 private and 13 public, collectively with 21 PET/CTs, and 89 SPECTs and SPECT/CTs. Production expertise from NECSA and iThemba LABS ensures access to various radiopharmaceuticals.

Barriers to utilization

Despite strengths, challenges persist. Dosimetry in clinical practice remains resource-intensive, affecting PRRT and PRLT. Limited access to radiopharmaceuticals outside metropolitan areas and financial concerns adversely impact the field. Nonetheless, the South African nuclear medicine landscape is making significant strides in research and theranostics.

Discussion

In the six featured countries, measurable strengthening of local radiotherapy and theranostics capacity has led to better clinical availability of services, though infrastructural gaps still marginalize many from the best possible care.

Belgium excels comparatively, but still triangulates some areas for RT and theranostics improvement. Brazil faces more distinct disparities, with advanced technologies preferentially available in private institutions due to low reimbursement in the public system. Similarly, Costa Rica has made progress in RT, but access to both RT and advanced nuclear medicine remains limited. Jordan has made national strides in cancer care, overall, largely centralized in the capital, Amman. With international collaboration, Mongolia is steadily improving its RT capabilities but, like elsewhere, challenges include staff shortages and limited access to advanced techniques including theranostics. South Africa is equipped with some state-of-the-art RT and nuclear medicine facilities, although heterogeneity in geographic availability, coupled with inadequate dosimetry practices, rank among persistent challenges in common with several other countries.

Ubiquitously, deficiencies could be more strategically assessed and addressed through furthering: innovative translational research, sustainably phased implementation with milestones, use of quality audits, educational exchange, multinational networking, and expansion of existing databases to inform decisions better.

Notably, cutting-edge technologies like multimedia, artificial intelligence, and virtual reality harbor great potential to further extend the benefits of RT and theranostics to cancer patients worldwide, even the hard-to-reach. Innovatively strengthening existing systems would also contribute to pandemic preparedness, as COVID-19 definitively strained already insufficient radiation medicine services worldwide.

The *Lancet Oncology* commission Expanding Global Access to Radiotherapy, published in 2015, quantified the investment to achieve global RT access equity by 2035 [35]. Synergistic evidence for upscaling medical imaging was presented in 2021 by a *Lancet Oncology* Commission on Medical Imaging and Nuclear Medicine, showing that the comprehensive combined scale-up of medical imaging; treatments (including medicines, surgeries, and RT); and care quality would prevent around 9.6 million deaths worldwide between 2020 – 2030 [36]. However, prior commissions did not assess the impact of implementing theranostics. These dynamic radiation medicine domains rank among cardinal drivers of personalized, safe, and highly-targeted precision medicine for many patients worldwide.

Aligned with both aforementioned commissions' Calls to Action and U.N. Sustainable Development Goal (SDG) 3 for health, the featured country vignettes summarize salient stories of establishing or improving RT and theranostics.

As cancer increases worldwide, collaboration of competent bodies – ministries of health, professional societies, the IAEA, and others – will foster more expedient implementation of oncologic imaging diagnostics and image-guided, often ionizing therapies. Cancer's devastating impact spotlights precisely why strengthening cancer management infrastructure, including radiation medicine, is elementary to national development envisaging "…the highest attainable standard of health as a fundamental right of every human being" enshrined in the WHO Constitution.

CRediT authorship contribution statement
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List of Abbreviations:

3D CRT	Three-Dimensional Conformal Radiation Therapy
ABFM	Association of Brazilian Medical Physics
AGAT-B	Apparatus for radiation therapy
AGAT-C	Apparatus for radiation therapy
AIDS	Acquired Immune Deficiency Syndrome
CBCT	Cone Beam Computed Tomography
CED	Coverage with Evidence Development
CICANUM	Atomic, Nuclear and Molecular Science Research Center
CNEM	National Nuclear Energy Commission of Brazil
COVID	CoronaVirus Disease
CT	Computed Tomography
DOTATATE	Dodecane Tetraacetic Acid
EBRT	External Beam Radiotherapy
FFF	Flattening Filter-Free
HDR	High Dose Rate
HIC	High-Income Country
IAEA	International Atomic Energy Agency
IAEA-DIRAC	International Atomic Energy Agency's Directory of Radiotherapy Centres
IBA	Ion Beam Accelerator
IGRT	Image-Guided Radiation Therapy
IMRT	Intensity-Modulated Radiation Therapy
IORT	IntraOperative Radiation Therapy
KHCC	King Hussein Cancer Center
LIC	Low-Income Country
LINAC	Linear Accelerator
LMIC	Low-Middle Income Country
MIBG	Iodine-123 Meta-IodoBenzylGuanidine
MLC	Multi-Leaf Collimator
MP	Medical Physicist
MR	Magnetic Resonance
NCCM	National Cancer Centre of Mongolia
NCD	Non-Communicable Diseases
NECSA	South African Nuclear Energy Corporation
NMP	Nuclear Medicine Physician
NTP	Non-Thermal Plasma
NuMeRI	Nuclear Medicine Research Infrastructure
PET	Positron Emission Tomography
PRLT	PSMA-targeted Radioligand Therapy
PRRT	Peptide Receptor Radionuclide Therapy
PSMA	Prostate-Specific Membrane Antigen
RCA	Regional Cooperative Agreements
RO	Radiation Oncologist
ROKUS-M	Type of gamma-beam therapy unit
RP	Radio Pharmaceuticals
RT	RadioTherapy
RTT	RadioTherapy Technologists
SBRT	Stereotactic Body Radiation Therapy
SPECT	Single Photon Emission Computed Tomography
SRS	Stereotactic Radiation Surgery
SRT	Stereotactic Radiotherapy
SUS	Sistema Único de Saúde (Brazilian Unified Health System)
TBI	Total Body Irradiation
TC	Technical Cooperation
UMIC	Upper-Middle Income Country
VMAT	Volumetric Modulated Arc Therapy

Table 1. Estimated medical professionals within the collective six countries per million inhabitants, stratified by World Bank country income groupings.

	Radiation Oncologists (ROs)	Nuclear Medicine Physicians (NMPs)	Medical Physicists (MPs)
High-Income Countries (HICs)			
Range	38.0-38.0	26.0-26.0	3.45-3.45
Mean (SD)	38.00 (0.00)	26.0 (0.00)	3.45 (0.00)
Median (IQR)	38.00 (0.00-0.00)	26.00 (0.00-0.00)	3.45 (0.00-0.00)
Upper-Middle-Income countries (UMICs)			
Range	3.01-6.01	1.00-4.00	0.47-0.44
Mean (SD)	4.16 (1.30)	2.50 (1.29)	2.02 (1.62)
Median (IQR)	3.82 (3.45-4.53)	2.00 (0.75-2.30)	2.09 (0.70-3.41)
Lower-Middle-Income Countries (LMICs)			
Range	2.69-2.69	2.00-2.00	0.30-0.30
Mean (SD)	2.69 (0.00-0.00)	2.00 (0.00-0.00)	0.30 (0.00-0.00)
Median (IQR)	2.69 (0.00-0.00)	2.00 (0.00-0.00)	0.30 (0.00-0.00)

HIC category includes Belgium.

UMICs include Brazil, Jordan, Costa Rica, and South Africa.

LMIC category includes Mongolia.
Low-Income (LI) category was not included.

* These numbers reflect medical physicists engaged in RT and nuclear medicine.

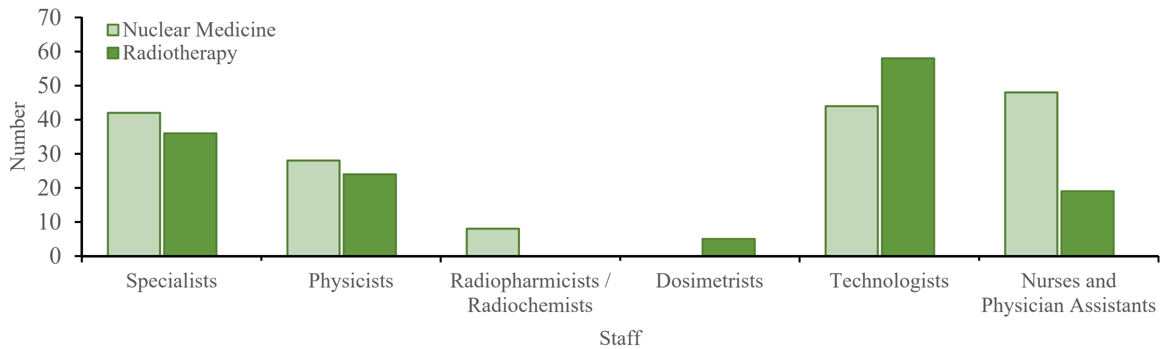
The data source is the International Atomic Energy Agency status of radiotheranostics and nuclear medicine staff survey.

Fig. 1. Theranostics: examples of radiotracers used for concurrent imaging and targeted therapy of given cancers. Graphic produced by the International Atomic Energy Agency (IAEA) in collaboration with Dr. Akram Al-Ibraheem of the King Hussein Cancer Center, Amman, Jordan.

	Target	Radiopharmaceutical [Diagnosis]		Radiopharmaceutical [Treatment]
Cancer		**SPECT**	**PET**	
Thyroid	Sodium symporters	[^{123}I] NaI	[^{124}I] NaI	[^{131}I] NaI
Prostate	Transmembrane protein	[^{99m}Tc]-PSMA	[^{68}Ga]-PSMA or	[^{177}Lu]-PSMA or
			[^{18}F]-PSMA	[^{225}AC]-PSMA
Neuroendocrine Neoplasms	Somatostatin receptor	[^{99m}Tc]-DOTATE	[^{68}Ga]-DOTA-peptide or	[^{90}Y]-DOTA-peptide or
			[^{18}F]-DOTA-peptide	[177Lu]-DOTA-peptide or
				[^{225}Ac]-DOTATATE
Phaechromocytoma / Neuroblastoma	Adrenal receptor	[^{123}I]-mIBG	..	[^{131}I]-mIBG
Primary and Metastatic Liver Neoplasms	Liver lesions	[^{99m}Tc]-MAA	..	[^{90}Y]-microspheres
Bone Metastases	Osteoblastic activity	[^{99m}Tc]-phosphonates	..	[^{89}Sr]-SrCl or
				[^{153}Sm]-EDTMP or
				[^{223}Ra]-RaCl

SPECT=single-photon emission CT. PET=positron emission tomography. PSMA= prostate-specific membrane antigen. MAA=macroaggregated albumin.

Fig. 2. Status of nuclear medicine and radiotherapy in Jordan (2022) as an exemplar.
Graphic produced by the International Atomic Energy Agency (IAEA) in collaboration with Dr. Akram Al-Ibraheem of the King Hussein Cancer Center, Amman, Jordan.



	Nuclear Medicine		Radiotherapy
Staff			
Specialists	42		36
Physicists	28		24
Radiopharmicists / Radiochemists	8		..
Dosimetrists	..		5
Technologists	44		58
Nurses and Physician Assistants	48		19
Equipment			
SPECT units	19	Linear accelerators	16
SPECT/CTs	3	CT simulators	6
PET/CTs	11	Brachytherapy units	3
Cyclotrons	2	X-knife	1
Cases to date (as measured in 2022)			
^{18}F-FDG-PET/CT	12104		
^{68}Ga-DOTATIC PET/CT	285		
^{68}Ga-PSMA PET/CT	246	External beam	4150
Theranostics SPECT	726	IMRT/VMAT	3526
^{131}I	846	SRS/SBRT	386
^{177}Lu-PSMA	44	3D CRT	208
^{177}Lu-DOTA	26	TBI	30
Other radiotheranostics (^{131}I-mIBG, ^{153}Sm, ^{89}Sr)	41	Brachytherapy	120

SPECT=single-photon emission CT. PET=positron emission tomography. IMRT=intensity-modulated radiation therapy. VMAT=volumetric modulated arc therapy. SRS=stereotactic radiosurgery. SBRT=stereotactic body radiotherapy. CRT=cardiac resynchronization therapy. TBI=total body irradiation.

Fig. 3. Estimated radiation oncologists per million inhabitants within the six collective countries.
Data were collected by the International Atomic Energy Agency through surveys.

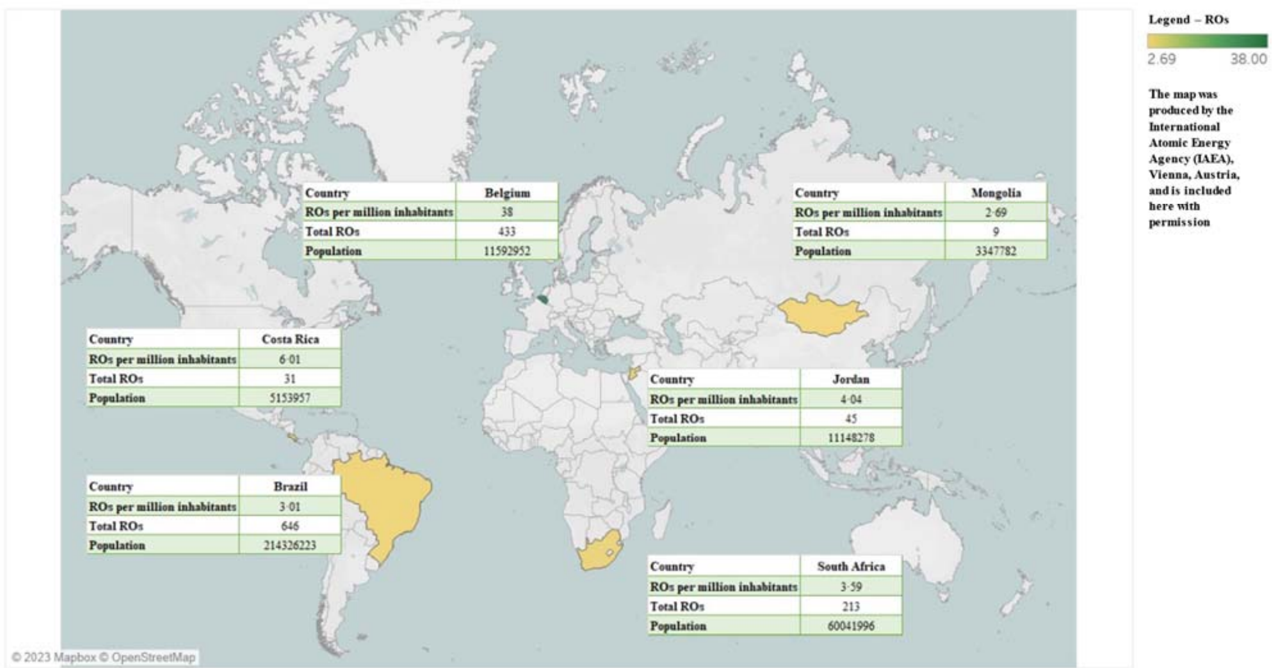


Fig. 4. Estimated nuclear medicine physicians per million inhabitants within the six collective countries.
Data were collected by the International Atomic Energy Agency status of radiotheranostics and nuclear staff survey.

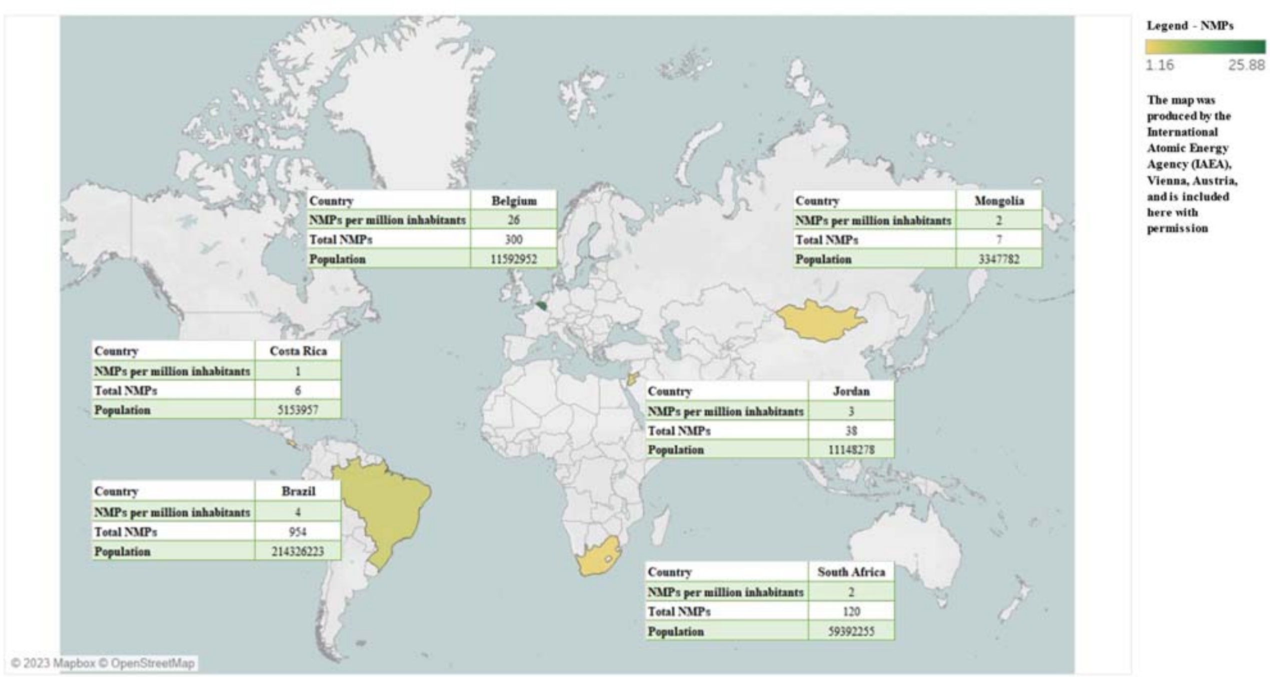


Fig. 5. Estimated medical physicists collectively for RT and Nuclear Medicine per million inhabitants within the six collective countries. Data were collected by the International Atomic Energy Agency status of radiotheranostics and nuclear staff survey.