Transformative Role of Nuclear Technologies in the Healthcare System of Pakistan: Advancements and Impact

Shazia Fatima[*]

Abstract

Nuclear technology and techniques have become the foundation of modern medicine, revolutionizing the diagnosis, treatment, and management of various pathologies and disease processes. The healthcare sector in Pakistan has also witnessed transformative developments, especially in the fields of oncology, cardiology, and neurology, among others, contributing directly to the United Nations (UN) Sustainable Development Goal 3 (SDG 3). Pakistan, from the outset, has continued to invest in healthcare facilities and developed a comprehensive network of 51 nuclear medicine facilities and 49 oncology centers, including 19 Atomic Energy Cancer Hospitals (AECHs). These centers offer state-of-the-art diagnostic and therapeutic services, including hybrid imaging with Positron Emission Tomography/Computed Tomography (PET/CT), Single Photon Emission Computed Tomography/Computed Tomography (SPECT/CT), conventional gamma cameras, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) mammography, and radiation treatment with teletherapy machines like linear accelerators, gamma and cyberknife, brachytherapy units as well as trailblazing theragnostic technologies. The production of indigenous radiopharmaceuticals, radioisotopes, and in-house cyclotron-based isotopes production has upgraded nuclear medicine facilities, including hospitals and diagnostic centers, by promoting self-reliance and reducing healthcare

[*]Shazia Fatima is MBBS, MS, FCPS, PGD, FANMB, CHPE, and serves as the Director General of the Nuclear Medicine and Oncology Directorate at the Pakistan Atomic Energy Commission (PAEC). She is also the President of Women in Nuclear Pakistan (WiN-P).

costs. In this regard, the Pakistan Nuclear Regulatory Authority (PNRA) ensures safety and standardization across these facilities through its regulatory framework and legislation. Although Pakistan has successfully established a comprehensive infrastructure of healthcare facilities using nuclear techniques, these facilities, primarily concentrated in major cities, are insufficient for its 250 million population. To overcome this challenge, there is a need for continued capacity building through infrastructure development, human resource training, and enhanced local isotope production. This article discusses Pakistan's historical developments in the field of healthcare, its current infrastructure, socioeconomic impact, and strategic direction of nuclear medicine and radiotherapy. This article further highlights the transformative role of nuclear technologies in improving public health outcomes and national healthcare resilience.

Keywords: Nuclear Applications in Healthcare Systems, Transformation in Understanding Diseases, Modern Medicines, PNRA, PAEC.

Introduction

Nuclear technology plays a key role in healthcare settings such as screening, early diagnosis, accurate treatment, and prognosis of several pathologies. Ionizing radiation, like X-rays, gamma rays, and particulates, enabling healthcare professionals to manage a wide array of diseases with remarkable precision. The integration of nuclear technology and techniques in healthcare infrastructure has led to an unprecedented transformation in understanding diseases at the molecular level and targeting them with unmatched precision. In addition, the integration of nuclear technology into medicine has enhanced diagnostic and therapeutic approaches worldwide.

In Pakistan's case, this transformation has been driven by sustained investment, strategic capacity building, and fruitful international partnerships. Moreover, the adoption of nuclear applications in healthcare systems has enabled early detection, accurate treatment, and significantly improved patient outcomes in Pakistan, particularly in the fields of oncology, cardiology, and neurology. The healthcare infrastructure in Pakistan has gradually incorporated nuclear techniques in the management of varied pathologies, particularly non-communicable diseases, especially cancer, cardiovascular ailments, and neurological disorders. This article explores the advent of nuclear technologies in the healthcare infrastructure of Pakistan, its current state, and future directions. This transformative journey directly aligns with the objectives of UNSDG 3,[1] which focuses on ensuring health and well-being for all age groups. Additionally, nuclear techniques play an instrumental role in achieving SDG 3.4 by enabling early detection and comprehensive treatment of non-communicable diseases (NCDs), particularly cardiovascular diseases and cancer. SDG 3.4 emphasizes the importance of reducing premature mortality from non-communicable diseases by one-third by the year 2030. This goal encompasses both prevention and treatment initiatives, along with a strong commitment to promoting mental health and overall well-being.

The field of medical diagnostics irreversibly changed with the discovery of X-rays by German physicist Wilhelm Conrad Roentgen in 1895.[2] Shortly after their discovery, X-rays were employed in the treatment of dermatological conditions, including skin cancers. Their diagnostic utility quickly expanded beyond skin ailments, offering unprecedented visual access to internal pathologies. Until the revolutionary advent of CT in 1971, conventional X-ray radiography remained the primary imaging tool in medicine.[3]

The mid-twentieth century brought another milestone with the discovery of radium, which led to its application in high-dose external beam radiation

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[1] World Health Organization, "SDG Target 3.4: Reduce by One Third Premature Mortality from Non-Communicable Diseases through Prevention and Treatment and Promote Mental Health and Well-Being," *World Health Organization*, https://www.who.int/data/gho/data/themes/topics/sdg-target-3_4-noncommunicable-diseases-and-mental-health

[2] Hyun Do Huh and Seonghoon Kim, "History of Radiation Therapy," *Progress in Medical Physics* 31, no. 3 (September 2020): 124–131, https://www.progmedphys.org/journal/view.html?doi=10.14316/pmp.2020.31.3.124

[3] Raymond A. Schulz, Jay A. Stein, and Norbert J. Pelc, "How CT Happened: The Early Development of Medical Computed Tomography," *Journal of Medical Imaging* 8, no. 5 (October 2021): 052110, https://doi.org/10.1117/1.JMI.8.5.052110

therapy and brachytherapy for cancer treatment. These innovations gave rise to the specialized field of radiotherapy by the 1930s.[4] Subsequently, in 1946, the production of radioisotopes at Oak Ridge Laboratory and the publication of pioneering research on radioactive iodine in the Journal of the American Medical Association (JAMA) marked the beginning of nuclear medicine as a recognized field.[5]

What began as a simple iodine-based treatment for thyroid disorders has now evolved into an advanced field known as theranostics. In this field, diagnostic and therapeutic techniques are integrated to personalize treatment, especially in fields like oncology and nuclear medicine. In addition, early imaging tools like rectilinear scanners have been succeeded by cutting-edge hybrid technologies such as PET-CT and SPECT-CT. These modern modalities enable detailed exploration of the underlying physiological and biochemical mechanisms of diseases such as cancer, cardiovascular disorders, neurological conditions, infections, inflammatory processes, and disorders of the lungs and kidneys.[6]

The continuous evolution of nuclear-based medical technologies is reshaping the global healthcare landscape at an unprecedented pace. It is now nearly inconceivable to envision a modern healthcare facility devoid of nuclear technologies, including radiology, nuclear medicine, and radiotherapy. These innovations are not only enhancing the quality of patient care but also contributing to broader access and operational efficiency within healthcare systems worldwide.

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[4] Gönül Kemikler, "History of Brachytherapy," *Turkish Journal of Oncology* 34, suppl. 1 (2019): 1–10, https://doi.org/10.5505/tjo.2019.1

[5] Saul Hertz and Arthur Roberts, "Radioactive Iodine in the Study of Thyroid Physiology VII: The Use of Radioactive Iodine Therapy in Hyperthyroidism," *Journal of the American Medical Association* 131, no.2(1946). https://doi.org/10.1001/jama.1946.02870190005002

[6] John Dennis Ehrhardt Jr. and Seza Güleç, "A Review of the History of Radioactive Iodine Theranostics: The Origin of Nuclear Ontology," *Molecular Imaging and Radionuclide Therapy* 29, no. 3 (2020): 88–97. https://doi.org/10.4274/mirt.galenos.2020.83703

Historical Development of Nuclear Technologies for Healthcare in Pakistan

Early Beginnings (1950s–1970s)

The application of nuclear technology in the health sector in Pakistan had a humble beginning in 1947 with an X-ray teletherapy machine being installed in Mayo Hospital, Lahore. Following the establishment of the Pakistan Atomic Energy Commission (PAEC) in 1956, a vision to harness nuclear science for energy, agriculture, industry, and healthcare emerged.[7] Thereafter, PAEC spearheaded the use of nuclear technologies in healthcare through its mandate for the peaceful, safe, and secure application of nuclear technology.

In 1960, Pakistan established its first nuclear medicine center, known as the Atomic Energy Medical Centre (AEMC) in Jinnah Postgraduate Medical Center (JPMC), Karachi. The center aimed to provide diagnostic and therapeutic services using radioactive isotopes for cancer treatment. Shortly thereafter, it was followed by the establishment of similar facilities by PAEC in Lahore, Hyderabad, Multan, Peshawar, among others. Most of these facilities initially provided nuclear medicine facilities with the help of a rectilinear scanner and uptake system. In the early 1970s, many radiation-based treatment machines and techniques like superficial and deep X-ray therapy equipment, strontium, gold wires and tubes, and a Co-60 teletherapy unit were developed. Historically, Pakistan inherited only a single X-ray-based teletherapy machine at the time of partition in 1947, which was placed in Mayo Hospital, Lahore.[8] Pakistan's first C0-60 unit was installed in the Nuclear Institute of Medicine and Radiotherapy (NIMRA), Jamshoro, in 1974. After becoming a member of the International Atomic Energy Agency (IAEA) in 1957, Pakistan began collaborating with it in the 1970s through its technical cooperation program.

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[7] Pakistan Atomic Energy Commission, "*The Pakistan Atomic Energy Commission Ordinance, 1965: Ordinance No. XVII of 1965*," Islamabad, 1983. https://inis.iaea.org/records/6nvmr-hf844
[8] Muhammad Mohsin Fareed, Muhammad Yahya Hameed, and Eileen Samuel, "Radiation Oncology Health Disparities in Pakistan," *The National Center for Biotechnology Information*, *Global Oncology* 9 (2023): e2300199, https://doi.org/10.1200/GO.23.00199

This collaboration was aimed at building capacity in the application of nuclear techniques in the health sector.[9]

Expansion and Institutionalization (1980s–1990s)

During the 1980s to 1990s, Pakistan steadily expanded its healthcare facilities by advancing nuclear technology in both public and private sectors. PAEC remained at the forefront by consistently establishing cancer treatment centers. These centers utilize advanced nuclear techniques for precise diagnosis and advanced management of noncommunicable diseases, especially cancer.

After the establishment of Pakistan's first nuclear medical center in 1960, PAEC expanded its mission of cancer care by adding five more cancer care facilities during the 1980s and 1990s. A significant landmark was the inauguration of the Nuclear Medicine, Oncology, and Radiotherapy Institute (NORI) Islamabad in 1983. Since then, the AECH-NORI has become the premier cancer care facility of Pakistan that offers cutting-edge cancer diagnosis, treatment, and academic training in the respective fields. It was also the first cancer care facility in the country to install a modern Linear Accelerator machine, paving the way to a new era of modern radiotherapy. Subsequently, NORI evolved as a comprehensive cancer care center, and in 2022, IAEA declared it as an Anchor Center under its "Ray of Hope" initiative for education and training in nuclear technology for cancer care.[10]

Another milestone was the establishment of the Institute of Nuclear Medicine and Oncology (INMOL) Lahore in 1984, which strengthened the national network of specialized cancer care institutions established by PAEC. Due to its achievements, the IAEA declared AECH INMOL a center

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[9] International Atomic Energy Agency, "*List of Member States*, International Atomic Energy Agency," https://www.iaea.org/about/governance/list-of-member-states

[10] Razya Khan, "NORI Cancer Hospital gets IAEA 'Anchor Centre," *Express Tribune*, 23 September 2023: https://tribune.com.pk/story/2437929/nori-cancer-hospital-gets-iaea-anchor-centre-status:also see, Amin Ahmed, "NORI cancer hospital designated 'anchor center' by IAEA," *Dawn*, 2023. https://www.dawn.com/news/1778038

of excellence and a referral center for Asia Pacific countries. AECH-INMOL is currently the largest cancer care facility within PAEC.[11] By adding these services, quality cancer care became accessible to populations that previously lacked adequate access.

During the 1990s, Pakistan's private sector also incorporated nuclear techniques in healthcare settings. Ziauddin Hospital in Karachi established the country's first private nuclear medicine in 1993.[12] Moreover, in 1994, Shaukat Khanum Memorial Cancer Hospital and Research Centre was inaugurated, which is Pakistan's first privately funded comprehensive cancer care facility providing an international standard of care to oncology patients. At the global level, there were many significant technological upgrades with the invention of gamma cameras for diagnostic scanning and widespread adoption of linear accelerators for radiotherapy, resulting in the improvement of disease detection and treatment capabilities.

Furthermore, Pakistan Institute of Nuclear Science and Technology (PINSTECH), a research and development facility of PAEC, helped in achieving self-sufficiency through the indigenous production of radioisotopes and radiopharmaceuticals. This journey began with the production of Iodine-131 (I-131) in the 1980s, which is used for the treatment of various thyroid pathologies. This was a major landmark toward reducing dependency on foreign sources and ensuring cost-effectiveness in treatment.[13]

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[11] Omar Yusuf, "IAEA Support Helps Pakistan to Conduct Novel Theranostic Interventions for the First Time, Expanding Cancer Care and Improving Outcomes", *International Atomic Energy Agency*, March 23, 2021. https://www.iaea.org/newscenter/news/iaea-support-helps-pakistan-to-conduct-novel-theranostic-interventions-for-the-first-time-expanding-cancer-care-and-improving-outcomes

[12] Maseeh uz Zaman and Nosheen Fatima, "Status of Nuclear Medicines in Pakistan,", *Pakistan Journal of Radiology,* Vol. 31 No. 3 (2021). https://www.pakjr.com/index.php/PJR/article/view/1435

[13]Mushtaq Ahmed, "Production of Radioisotopes in Pakistan Research Reactor: Past, Present and Future," paper presented at the IAEA Technical Meeting, Vienna, 2010 (Islamabad: Pakistan Institute of Nuclear Science and Technology), 4–13, https://www-pub.iaea.org/MTCD/Publications/PDF/SupplementaryMaterials/TECDOC_1713_CD/template-cd/datasets/papers/Mushtaq%20Production%20of%20RI%20PARR%20Mar2011.pdf

In the late 1990s, PINSTECH advanced its facilities by successfully developing the Molybdenum-Technetium (Mo-Tc) generator system, which is used in the daily operations of nuclear medicine departments for a wide range of diagnostic procedures. Simultaneously, PINSTECH also developed radiopharmaceutical kits, which are used in the imaging of various organs and disease processes. These initiatives collectively contributed to enhanced self-reliance, reduced operational costs, and uninterrupted supply chains for nuclear medicine centers across Pakistan.[14] Currently, PINSTECH is the major supplier of radioisotopes, radiopharmaceutical kits, and Mo-Tc generators to public and private sector nuclear medicine facilities across Pakistan.

The Era of Modernization and Technological Advancement (2000s–Present)

Nuclear technology in the healthcare sector of Pakistan entered a new era of development in the twenty-first century. This new era was marked by the installation of cutting-edge diagnostic and therapeutic equipment. In nuclear medicine, the most notable advancements were the development of hybrid imaging systems, including PET/CT and SPECT/CT. These hybrid systems provide high-resolution images with anatomical precision that help clinicians to visualize the underlying metabolic activities combined with anatomical aspects of diseases, resulting in enhanced diagnostic accuracy.

In 2009, Pakistan had its first public sector PET-Cyclotron facility at INMOL Lahore, a monumental landmark that helped in the local production of short-lived radiotracers used in PET imaging. This development transfigured cancer care in Pakistan, in addition to providing other benefits like reduced radioisotope costs and minimized reliance on imports.

Establishment of Cyberknife radiosurgery facility at Jinnah Postgraduate Medical Centre (JPMC) Karachi in 2012, further strengthened the usage of

[14] J. H. Zaidi, Mohammad Wasim, Mohammad Arif, and Mushtaq Ahmad, "Development of Radiochemistry in Pakistan – 1960 to 2010," *Radiochimica Acta* 100, no. 8–9 (April 2014): 555–568, https://www.researchgate.net/publication/236013073_Radiochemistry_in_Pakistan

nuclear technology for cancer care. Cyberknife is a non-invasive radiation treatment modality that allows for ultra-precise treatment of small-sized unapproachable tumors. The addition of Cyberknife expanded the range of treatment options for different types of cancers, which were once considered inoperable or difficult to manage with conventional radiotherapy.

By the mid-2010s, PAEC had established 18 cancer care hospitals, providing nuclear medicine and radiotherapy services to all provinces and major cities of Pakistan. This network has not only improved accessibility but also contributed to early diagnosis and better management outcomes for countless patients. These AECHs treat more than one million patients annually, with a constant increase in numbers every year.[15]

Along with clinical advancements, Pakistan has also excelled as a regional leader in nuclear medicine education and training. Several AECHs have gained national, international, and regional recognition, including endorsements from the IAEA and other local regulatory bodies, establishing the country as the center point for capacity-building and professional development in nuclear techniques.

Current Infrastructure and Facilities

Rise of Nuclear Medicine: From Modest Beginnings to a National Network

With a humble beginning in 1960, nuclear medicine has been transformed into a thriving network of nearly 51 nuclear medicine setups across Pakistan. This remarkable growth is a testament to the country's sustained commitment to integrating nuclear technology into healthcare infrastructure. Today, nuclear medicine is a critical pillar of diagnostic and therapeutic services nationwide, along with conventional and modern radiology.

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[15] Begum, N., Nasreen, S. and Shah, A.S. (2012) "Quantification of Trends in Radiation Oncology Infrastructure in Pakistan," 2004-2009. *Asia-Pacific Journal of Clinical Oncology,* 8, 88-94, http://dx.doi.org/10.1111/j.1743-7563.2011.01435

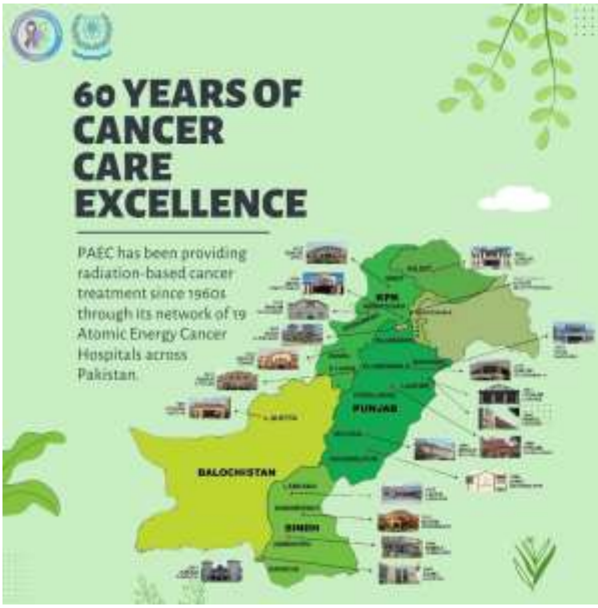

Fig. 1 Pakistan Atomic Energy Commission's Cancer Care Hospitals

The field of nuclear cardiology has seen substantial expansion with the introduction of sophisticated hybrid imaging SPECT/CT and PET/CT systems. Currently, 21 specialized centers are offering nuclear cardiology services across the country, helping in the early diagnosis and effective management of ischemic heart disease and other cardiovascular conditions. These centers utilize non-invasive nuclear imaging techniques that have improved the accuracy of cardiac assessments and disease management.

Modern nuclear medicine with hybrid imaging technologies and techniques, such as PET/CT and SPECT/CT, has added precision to the traditional diagnostic methods. Artificial intelligence (AI) incorporated in modern-day machines is proving to be a quantum leap in diagnostic capabilities. These innovations have resulted in increased image resolution and detailed insights into both anatomical and functional aspects of diseases. Nuclear Medicine has now become the integration of hybrid imaging, which has elevated the diagnostic capabilities of nuclear medicine to a level where it often becomes the decisive factor in clinical management, especially in complex cases like cancer.

Since the introduction of the first PET imaging facility in Pakistan in 2009, molecular imaging has gradually grown. Over the past 16 years, the country has established 15 PET and molecular imaging facilities, supported by 13 cyclotron facilities responsible for producing the short-lived radiotracers essential for PET imaging. This infrastructure is continually expanding, with a few more PET centers currently in the planning and development phase. At present, there are a total of 20 PET/CT cameras functioning in the country.

Likewise, the installation of approximately 25 SPECT/CT gamma cameras has further fortified the diagnostic arsenal available to nuclear medicine practitioners. These devices offer highly precise imaging across a wide spectrum of diseases, enabling timely and accurate diagnoses in oncology, cardiology, neurology, and other disciplines.

As reported by the IAEA's Medical Imaging and Nuclear Medicine Global Resources Database (IMAGINE), Pakistan has fewer than one PET scanner per million inhabitants, and similarly, the availability of SPECT gamma cameras stands at less than 2.5 units per million people.[16] This is significantly less than developed countries; however, there is a gradual improvement in the last few years, and the situation will improve in the years ahead.

Therapeutic Advances and the Emergence of Theranostics

The growth of nuclear medicine in Pakistan has not been limited to diagnostics alone. Therapeutic nuclear medicine has also witnessed a period of rapid advancement, driven by the approval and clinical adoption of novel radioisotopes for the treatment of various cancers. These agents are now used to target tumors with minimal impact on surrounding healthy tissue, offering patients safer and more effective treatment options.

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[16] International Atomic Energy Agency, *IAEA DIRAC - International Atomic Energy Agency,* https://www.iaea.org/resources/databases/dirac

Theranostics is a concept that combines diagnostics and therapy using matched pairs of radioisotopes. Recent advances in matched radioisotopes and radiopharmaceutical production have transformed cancer therapy. However, the theranostic concept is not new, as Iodine-131 (I-131) has been a longstanding theranostic agent used in nuclear medicine since the start of the specialty. However, the development of numerous new radiopharmaceutical and radioisotopes pairs has opened new avenues for therapeutic nuclear medicine, which has dramatically expanded the scope of nuclear medicine.

Lutetium-177 (Lu-177) based therapies, using peptides like prostate surface membranous antigen (PSMA) and DOTATAE have changed the treatment landscape for neuroendocrine tumors and metastatic prostate cancer. These therapies received Food and Drug Administration (FDA) approvals in 2020 and 2023, respectively, as standard-of-care treatments in clinical oncology. In Pakistan, AECH-INMOL established the first full-fledged theranostic facility in 2017, where Gallium-68 (Ga-68) PET imaging is paired with Lu-177-labeled therapeutic radiopharmaceuticals.[17] Since the establishment of this theranostic facility, the center has successfully treated over 500 cancer patients using state-of-the-art protocols.

Thus far, six AECH have started theranostic treatment modality, namely INMOL, NORI, The Institute of Radiotherapy and Nuclear Medicine (IRNUM), Karachi Institute of Radiotherapy and Nuclear Medicine (KIRAN), PINUM Cancer Hospital, and Gujranwala Institute of Nuclear Medicine and Radiotherapy (GINUM). Additionally, three private sector hospitals have also begun offering theranostic services, demonstrating growing confidence and investment in this domain from both public and private healthcare institutions.

The range of new radioisotopes has further broadened the therapeutic options. These include Actinium-225 (Ac-225), labeled PSMA for advanced

[17] "First Theranostic Lab at INMOL Hospital," *The Nation*, November 7, 2017. https://www.nation.com.pk/07-Nov-2017/first-theranostic-lab-at-inmol-hospital

prostate cancer, Yttrium-90 (Y-90) TheraSphere for liver tumors, and various beta and alpha emitters used in bone pain palliation and metastatic cancer therapy. These agents have given flexibility for clinicians to personalize cancer treatment, improve patient quality of life, and extend survival.

Evolution and Expansion of Radiation Therapy in Cancer Care

The role of nuclear technologies in cancer management extends far beyond diagnostics; it is at the very heart of treatment for a significant portion of patients. Globally, and in Pakistan alike, approximately 70% of cancer cases require external beam radiation therapy (EBRT), also known as teletherapy, either as a standalone treatment or in combination with chemotherapy or hormonal therapy. Radiation therapy has emerged as a cornerstone in oncological care, especially in solid tumors, where it delivers curative and palliative outcomes with increasing precision and safety.

According to GLOBOCAN,[18] in 2022, there were about 0.18 million new and 0.39 million prevalent (5-year) cancer patients in Pakistan.[19] According to Radiotherapy and Theranostics, a Lancet Oncology Commission,[20] and the Directory of Radiotherapy Centers (DIRAC),[21] there are 1-3 radiotherapy machines for a population of 1 million in Pakistan. Although this number still needs a huge improvement, there has been a constant improvement in the radiotherapy landscape of Pakistan.

Indeed, Pakistan's journey in this field reflects a remarkable transformation. What began with a solitary X-ray machine decades ago has now evolved

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[18] Global Cancer Observatory, *Global Cancer Fact Sheet: World* (Lyon, France: International Agency for Research on Cancer, 2023), https://gco.iarc.who.int/media/globocan/factsheets/populations/900-world-fact-sheet.pdf

[19] J. Ferlay et al., *Global Cancer Observatory: Cancer Today*, Lyon, France: International Agency for Research on Cancer. https://gco.iarc.who.int/media/globocan/factsheets/populations/586-pakistan-fact-sheet.pdf

[20] May Abdel-Wahab et al., "Radiotherapy and Theranostics: A Lancet Oncology Commission," *The Lancet Oncology*, https://www.thelancet.com/journals/lanonc/article/PIIS1470-2045(24)00407-8/abstract

[21] International Atomic Energy Agency, *IAEA DIRAC - International Atomic Energy Agency*. https://www.iaea.org/resources/databases/dirac

into a sophisticated national infrastructure featuring cutting-edge technologies like Cyberknife and Linear Accelerators (LINACs).[22] PAEC, with its 19 cancer hospitals, is the largest public-sector cancer treatment network in Pakistan. PAEC is leading the technological revolution in cancer care across the country. These centers are equipped with state-of-the-art facilities for radiation treatment planning, simulation, and radiation treatment delivery, providing hope to thousands of cancer patients every year. In addition to the PAEC cancer care network, there are about 30 cancer care facilities offering medical or radiation treatment to cancer patients.

In terms of equipment, Pakistan's radiotherapy facilities encompass an array of teletherapy machines. Traditional Cobalt-60 (Co-60) machines,[23] once the backbone of radiation treatment, are still in use in many public and private sector hospitals, especially in resource-limited settings. These machines continue to serve both palliative and curative purposes, particularly in regions where advanced technology is still lacking. However, technological progress has seen a widespread shift toward Linear Accelerators, which now number around 58 units, including single and dual-energy LINACs.

This transition is not merely an upgrade in hardware, but it's a game-changer in radiation treatment. Modern radiotherapy techniques such as Intensity-Modulated Radiation Therapy (IMRT), Image-Guided Radiation Therapy (IGRT), Volumetric-Modulated Arc Therapy (VMAT), Stereotactic Radiosurgery (SRS), and Stereotactic Body Radiation Therapy (SBRT) are used in many cancer centers in Pakistan.[24] These advanced techniques result

[22] Muhmmad Mohsin Fareed et al., "Evolution of Radiation Oncology in Pakistan," *International Journal of Radiation Oncology, Biology, Physics* 105, no. 4 (2019): 766–772, https://www.redjournal.org/article/S0360-3016(19)30648-0/fulltext
[23] B. J. Healy et al., "Cobalt-60 Machines and Medical Linear Accelerators: Competing Technologies for External Beam Radiotherapy," *Clinical Oncology* 29, no. 2 (2017): 110–115, https://doi.org/10.1016/j.clon.2016.11.002
[24] Franjo Cmrečak, Iva AndraŠek, Meliha Solak Mekić, Mirna Ravlić, and Lidija Beketić-Orešković, "Modern Radiotherapy Techniques," *Libri Oncologici* 47, no. 2–3 (2019): 91–97, https://doi.org/10.20471/LO.2019.47.02-03.17

in remarkable precision in radiation delivery, delivering high radiation doses to tumors while sparing healthy tissues, improving patient outcomes.

Further advancement in radiation treatment is through the installation of Cyberknife and Gamma Knife systems in both public and private sector hospitals. This highly sophisticated equipment is specially designed to treat small and deeply located tumors with extraordinary precision. Utilizing highly focused beams of radiation, these machines can often achieve therapeutic effects in just a few treatment sessions, as opposed to the twenty to thirty treatment sessions required with conventional teletherapy machines. Currently, six such systems are operational in Pakistan, offering targeted radiation treatment for conditions such as brain tumors, spinal lesions, and early-stage cancers in other critical areas.

Additionally, there is another advanced teletherapy machine, the MR LINAC, a hybrid machine, that combines MRI with a Linear Accelerator.[25] This cutting-edge technology allows real-time imaging during treatment. Three MR LINAC systems have recently been installed in leading hospitals of Sindh province, marking Pakistan's venture into the global elite of radiotherapy providers.

Regulation and Safety

The PNRA plays a pivotal role as the guardian of safety and standardization in treatment and diagnosis using ionizing radiation.[26] PNRA has been mandated to oversee the responsible use of radiation in medical and healthcare settings. It ensures that all healthcare institutions using nuclear techniques operate within a framework of stringent licensing, regulatory compliance, and international safety protocols, particularly those laid out by the IAEA. From the quality assurance (QA), quality control (QC), calibration of diagnostic equipment like gamma cameras, SPECT/CT, and

[25] Muhammad Atif Mansha and Shahzaib Naeem, "Welcoming the First Magnetic Resonance-Integrated Linear Accelerator in Pakistan," *Journal of the College of Physicians and Surgeons Pakistan* 35 (2025): 481, https://doi.org/10.29271/jcpsp.2023.04.481
[26] Pakistan Nuclear Regulatory Authority, "Radiation Protection," https://www.pnra.org/r-safety.html

PET scanners, to the use of high-energy radiation machines for cancer treatment including Co-60 units, LINACs, and Cyberknife system, PNRA's oversight ensures that the benefits of these technologies are delivered without compromising human health or environmental safety.[27] PNRA not only facilitates the safe integration of nuclear science into medicine but also strengthens public trust in technologies that are vital to the diagnosis and treatment of cancer, cardiovascular diseases, and other life-threatening conditions.

Socioeconomic Impact

Applications of nuclear techniques have revolutionized the health sector in many ways. First and foremost, the diagnosis of diseases has almost totally shifted to radiation techniques or technologies. Whether it's cancer detection, cardiac diseases, renal pathologies, GIT related ailments, neurological disorders, musculoskeletal or joint pathologies, infection or inflammation, nuclear medicine and radiological imaging techniques, using radiation has become a part of the many diagnostic guidelines. These modern modalities ensure early disease detection, help in the assessment of the efficacy of the treatment, and guide the recurrence of the disease. This has led to improved quality of life and enhanced overall survival. Early detection and tailored management using these techniques have a high impact on the healthcare sector. These advancements help in cost saving through early detection and comprehensive management by facilitating timely intervention and reducing the need for prolonged or invasive therapies. Training and employment opportunities have increased in fields like radiotherapy, medical physics, radio pharmacy, and nuclear medicine technology.

Nuclear medicine and radiological techniques have significantly transformed disease detection and Pakistan's healthcare landscape, offering advanced diagnostic and therapeutic options that enhance patient outcomes

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[27] International Atomic Energy Agency, *Quality Assurance for SPECT Systems*, Human Health Series No. 6 (Vienna: IAEA, 2009). https://www.iaea.org/publications/8119/quality-assurance-for-spect-systems

and contribute to the nation's economy through cost savings. The PAEC has been at the forefront of integrating nuclear technology into healthcare. Through its established 19 AECHs across the country, it provides diagnostic and treatment services to over 40,000 new cancer patients annually and performs approximately one million diagnostic and treatment procedures each year.[28] These facilities utilize state-of-the-art imaging technologies, including SPECT and PET scans, enabling early and accurate disease detection.[29] About 200,000 nuclear medicine procedures are performed annually across Pakistan for diagnosing various pathologies, including cancer.[30]

In radiotherapy, Pakistan has made remarkable advancements. Currently, there are 58 radiation treatment units in the country, comprising 27 linear accelerators and 31 Cobalt-60 machines. These facilities have improved access to cutting-edge cancer treatment. In PAEC cancer hospitals, nearly 75000 radiotherapy procedures were performed in 2024.

The expansion of nuclear medicine and radiological services also has economic implications. By facilitating early diagnosis and effective treatment, these technologies reduce the burden of disease, lower healthcare costs, and enhance workforce productivity. Moreover, the development of local expertise and infrastructure in nuclear medicine has fostered job creation and technological innovation, contributing to economic growth.

To sum up, the integration of nuclear medicine and radiological techniques into Pakistan's healthcare system has not only improved patient care but also supported economic development through cost savings, job creation, and technological advancement.

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[28] Associated Press of Pakistan, "PAEC Serve over 40,000 New Cancer Patients Each Year," *APP*. https://www.app.com.pk/national/paec-serve-over-40000-new-cancer-patients-each-year/

[29] Fawaz F. Alqahtani, "SPECT/CT and PET/CT, Related Radiopharmaceuticals, and Areas of Application and Comparison," *Saudi Pharmaceutical Journal* 31, no. 3 (2023): 279–291, https://doi.org/10.1016/j.jsps.2022.12.013

[30] S. J. Khurshid, "Nuclear Medical Centers of PAEC," *The Nucleus* 42, no. 1–2 (2005): 93–96, http://thenucleuspak.org.pk/index.php/Nucleus/article/view/1051/704

Positioning Pakistan's Healthcare Facilities within the Global Landscape

Healthcare infrastructure involving nuclear technologies and techniques has significantly evolved in Pakistan since its independence. However, considerable gaps continue to exist due to the high capital cost involved in procuring and running these high-end technologies. Pakistan has most of the modern diagnostic and treatment equipment commonly used globally, surpassing many LMIC; however, cutting-edge equipment remains an unfulfilled aspiration.

When we compare the nuclear medicine landscape in Pakistan with global standards, it is satisfying to document tremendous growth from a rectilinear scanner to hybrid and molecular imaging technology, providing information at the cellular level. Although Pakistan has attained most of the high-end technology and techniques in Nuclear Medicine and related fields but comparison with the Western world shows that we still are deficient in equipment like Whole body PET system, PET-MR, SPECT-MR. Although these machines are highly specialized and are beneficial in very few pathologies but there should be availability of this equipment in any of our highly specialized nuclear Medicine setups. Acquisition of these innovative technological inventions is hindered due to the high capital cost of this equipment.

Radionuclide therapies (RNTs) and theranostic techniques are in vogue. Although 5-6 hospitals in Pakistan are offering established RNT/Theranostic techniques to patients, we are lagging in the production of novel radioisotopes and radiopharmaceuticals, which are currently available for experimental and clinical use globally. New radioisotopes like Ac225, Bi212/213, Cu 64/ Cu 67, Rd223, Tb (149, 152, 155 and 161), Zr89, Y90, etc, which are currently used globally for diagnosis and treatment, are not available in Pakistan. We direly need indigenous production to save huge import costs and to benefit patients with these specialized radioisotopes for the management of various cancers. PINSTECH is diligently working to supply the currently utilized Lu-177 for therapeutic purposes.[31] However, the growing demand from various nuclear medicine centers necessitates an expansion of the current production capacity.

In the field of radiotherapy, despite an inadequate ratio of population to EBRT (External Beam Radiotherapy) machines, Pakistan does possess several state-of-the-art teletherapy units, starting from a time-tested C0-60 teletherapy machine to highly precise Robotic Cyberknife machines. These high-end units are mainly limited to the bigger cities like Karachi, Lahore, Islamabad, and their distribution in the country is skewed. Pakistan, despite having most of the teletherapy machines, lacks advanced particle therapy technologies such as proton therapy, Carbon ion radiotherapy (CIRT), and Boron Neutron Capture Therapy (BNCT). This extremely expensive equipment uses sophisticated techniques for radiation treatment, but these are currently unavailable in Pakistan. Currently, a proton therapy unit is under consideration, but it will take a few years before it can be available for therapeutic purposes to cancer patients in Pakistan.

Advanced teletherapy techniques like Flash radiotherapy,[32] novel three-stage nanotechnology- chemo-radiation combinatorial approach, interoperative radiotherapy, and combined photodynamic therapy are showing promising and favorable results in comparison with conventional techniques.[33] However, these techniques are still not available in the country. These techniques can be implemented after the necessary infrastructure development.

[31] Pakistan Atomic Energy Commission, “Pakistan: Strategy for Self-Reliance and Sustainability of Radiopharmaceutical Production Facility in Pakistan,” in *Sustainability and Self-Reliance of National Nuclear Institutions: Proceedings of a Workshop*, IAEA-TECDOC-1943 (Vienna: International Atomic Energy Agency, 2020), 77–84. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1943web.pdf

[32] R. Tang, J. Yin, Y. Liu, and J. Xue, “FLASH Radiotherapy: A New Milestone in the Field of Cancer Radiotherapy,” *Cancer Letters* 587 (April 10, 2024): 216651, https://doi.org/10.1016/j.canlet.2024.216651

[33] K. Koka, A. Verma, B. S. Dwarakanath, and R. V. L. Papineni, “Technological Advancements in External Beam Radiation Therapy (EBRT): An Indispensable Tool for Cancer Treatment,” *Cancer Management and Research* 14 (April 11, 2022): 1421–1429, https://doi.org/10.2147/CMAR.S351744

In addition, AI in diagnostic imaging and treatment has transformed the healthcare landscape. Most of the diagnostic and treatment equipment is already laced with advanced AI software. Pakistan needs substantial investment in the AI sector to develop AI algorithms based on local data, which will aid in swift and accurate diagnosis and treatment.

Furthermore, Pakistan needs to strengthen the nuclear technology-based diagnostic and therapy network, as currently our machine-to-population ratio is dismal even in comparison with LMIC. Pakistan currently has 19 PET scanners. Optimally, a population of one million requires at least 1-2 scanners,[34] meaning approximately 230 scanners are needed for the entire population, which does not seem to be possible shortly. The situation is similar in teletherapy equipment. According to a comprehensive study published in Lancet Global Health, there is a huge gap (58 existing units compared to ˜200 machines needed) in radiation treatment machines in the country. So, in addition to upgrading technological infrastructure, there is an urgent need to expand and increase the number of diagnostic and treatment machines. There should also be a homogeneous distribution of facilities across the country instead of concentration in larger cities for better access to patients living in remote areas of Pakistan.

Although Pakistan has made significant progress since its independence, access to nuclear medicine and radiotherapy facilities remains uneven, with rural and underdeveloped areas still underserved. Moreover, some novel radiopharmaceuticals, especially therapy-related ones, are not locally available; hence, they must be imported. Lastly, keeping abreast of the rapidly evolving technological horizons warrant continuous training of the workforce.

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[34] Agency, International Atomic Energy (IAEA). 2023: *https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINEMaps4.html.* Jan. https://www.iaea.org/resources/hhc/nuclear-medicine/databases/imagine#section-5

Strategic Priorities

To cater to the ever-increasing utilities and demands of these nuclear technologies in healthcare, Pakistan needs to expand its network of healthcare facilities with these specialized techniques to Balochistan, rural Punjab, Khyber Pakhtunkhwa (KPK), and Sindh. Pakistan needs further investment in local isotope production and cyclotron facilities. One way of enhancing these capabilities is by strengthening public-private partnerships for sustainable growth. Additionally, Pakistan needs to leverage emerging technologies by integrating AI into imaging interpretation and radiation planning.

Despite significant advancements, challenges persist, including the need for more widespread access to nuclear medicine services, especially in remote areas. Future efforts should focus on expanding infrastructure, enhancing local production of radiopharmaceuticals, and fostering international collaborations to stay abreast of technological innovations.

Conclusion

The integration of nuclear applications into Pakistan's healthcare system has had a profound and lasting impact. From humble beginnings in the 1960's to the establishment of world-class institutions offering cutting-edge diagnostics and therapies, Pakistan's progress is commendable. As the country continues to face rising cancer and cardiac disease rates, nuclear medicine will play a central role in managing this burden. Sustained support, innovation, and equitable access are critical for its future trajectory.