Guest Editorial

DAE's Leadership in Advancing National Healthcare through Ionizing Radiation

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Introduction: Ionizing radiation and nuclear medicine (i.e., use of radioactive substances known as radionuclides) are integral to modern healthcare, offering critical tools for diagnosing, treating, and managing a wide range of medical conditions, significantly enhancing patient care and outcomes. These technologies are indispensable in the fight against cancer, supporting everything from screening and detection to diagnosis, treatment, and palliative care. Beyond oncology, they are equally crucial for diagnosing and treating a wide range of conditions, including cardiovascular and neurological diseases, through routine medical imaging and advanced treatments. In developed countries, which represent about a quarter of the global population, approximately one in 50 people undergo diagnostic nuclear medicine procedures annually [1]. Globally, over 10,000 hospitals use radioisotopes for medical applications, with around 90% of these procedures dedicated to diagnosis. In contrast, therapeutic use of radioisotopes is less frequent, occurring at about one-tenth the rate of diagnostic procedures. This editorial explores the role of the Department of Atomic Energy (DAE) in advancing healthcare through the use of ionizing radiation in the country.

Historical Evolution of Nuclear Medicine: Dr. Homi Jehangir Bhabha, the founding father of India's nuclear program, played a pivotal role in the formation of the Atomic Energy Commission (AEC) in 1948. The growth of nuclear medicine in India is deeply intertwined with its atomic energy program. In 1954, Dr. Bhabha founded the Atomic Energy Establishment, Trombay (AEET), which was renamed Bhabha Atomic Research Centre (BARC) in 1967. BARC developed India's first research reactor, APSARA, became operational in 1956, followed by the CIRUS reactor in 1960. These reactors enabled the indigenous production of medical radionuclides like ^{131}I, ^{32}P, and ^{51}Cr, particularly enhancing clinical research with radioiodine (^{131}I). Through its extensive R&D efforts, BARC started producing and supplying radioisotopes and radiopharmaceuticals to Indian hospitals in the early 1960s. Since 1989, the Board of Radiation and Isotope Technology (BRIT) has become a key supplier of nuclear medicine throughout India. Dr. Bhabha also established a radioisotope laboratory near Grant Medical College in Byculla and secured space at Tata Memorial Hospital for the Radiation Medicine Centre (RMC), a division of BARC, which was inaugurated on September 3, 1963. Dr. K.N. Jeejeebhoy was appointed as the head, with Dr. R.D. Ganatra, Dr. S.M. Sharma, and Dr. H. DaCosta as the first physicians [2]. Nobel Laureate Dr. Ernest Lawrence donated the initial instruments for the facility. Concurrently, in 1956, the Ministry of Defence established the Radiation Cell at Safdarjung Hospital in Delhi for biomedical research using radioisotopes, led by Lt. Col. Dr. S.K. Mazumdar [2]. This eventually led to the creation of the Institute of Nuclear Medicine and Allied Sciences (INMAS), with the foundation stone laid in 1961 and the official dedication in 1964. The RMC has evolved into a premier R&D center for nuclear medicine and was the first in the country to install a medical cyclotron in 2002. Since then, many medical cyclotrons have been established across India, producing vital radioisotopes for diagnostic and therapeutic nuclear medicine procedures. Figure 1 provides an overview of how ionizing radiation and radioisotopes are generated, processed, and used in healthcare applications.

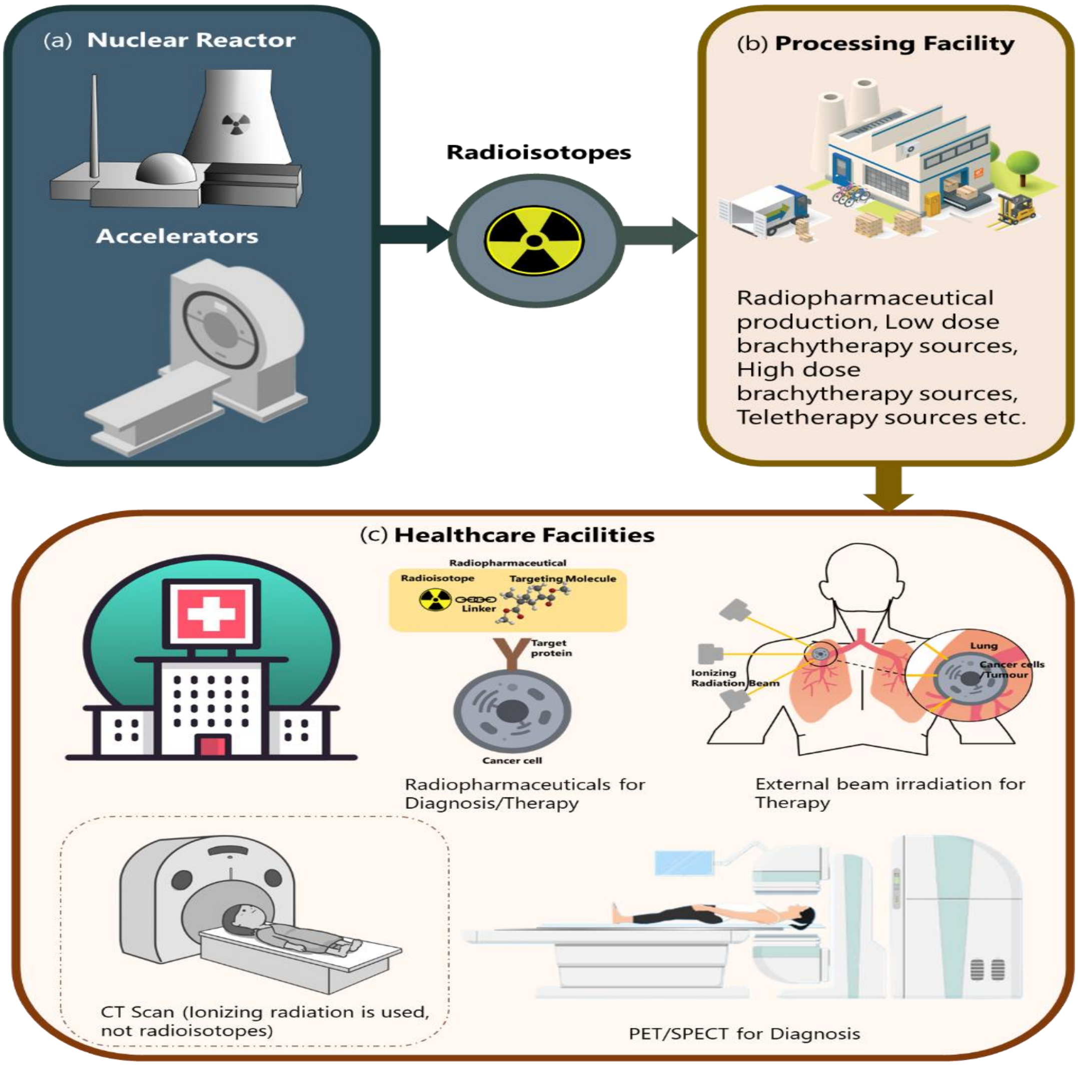

Figure 1. An illustration of how radioisotopes are produced, processed and used in healthcare. (a) Shows where radioisotopes are produced – either in nuclear reactors, such as Dhruva at BARC or accelerators – for their production for healthcare applications. (b) These radioisotopes need to be processed into usable products such as radiopharmaceuticals, brachytherapy sources, teletherapy sources etc. This happens at processing facilities such as BRIT. (c) Once processed, the various products are supplied to healthcare facilities for their varied uses as depicted in figure.

Ionizing Radiation for Diagnosis: Quality healthcare depends on accurate diagnosis and effective treatment assessment, with radiation imaging playing a vital role in this process. Diagnosis can be approached in two primary ways: externally, using ionizing radiation in diagnostic radiology, or internally, through radioisotopes introduced into the body, known as diagnostic nuclear medicine [3]. **Radiography**, a common diagnostic radiology tool, uses X-rays to capture images of bones, vessels, soft tissues, and organs. It is particularly useful for assessing the respiratory system for conditions such as tuberculosis, pneumonia, and lung diseases, as well as cardiac issues like cardiomegaly and pericardial effusions. Radiography is also critical for early fracture detection, especially in emergency and ICU settings where patient mobility is limited. **Mammography**, another key diagnostic technique, employs X-ray imaging of the breast for early breast cancer detection. It is also used to evaluate breast pathologies and monitor patients undergoing breast cancer treatment. Similarly, fluoroscopy provides real-time X-ray imaging of organs or structures, offering lower radiation doses compared to CT scans. Although it provides less detailed images, fluoroscopy is valuable for both diagnostic and therapeutic procedures. **Computed Tomography (CT)** scans use X-rays to create cross-sectional images of the body. A CT scanner consists of an X-ray source and detectors that rotate around the patient to produce detailed images. CT scans are crucial in trauma cases for identifying intracranial bleeds, brain damage, fractures, and internal injuries not visible externally. They are also invaluable in oncology for locating tumors and assessing their relationship to surrounding structures, aiding in treatment planning. **Diagnostic Nuclear Medicine** on the other hand involves administering radioisotope-labelled pharmaceuticals to patients for diagnostic or therapeutic purposes. Diagnostic tracers typically use gamma-emitting radionuclides like technetium-99m (^{99m}Tc) or positron-emitting ones like fluorine-18 (^{18}F). These radiopharmaceuticals localize to specific organs, emitting radiation from within the body that can be detected using radiation detectors. This principle underlies many nuclear imaging procedures such as positron emission tomography (PET) and single-photon emission computerized tomography (SPECT). The metabolic tracer ^{18}F fluorodeoxyglucose (FDG) has become essential in PET imaging, particularly in oncology.

Ionizing Radiation for Therapy: Radiation therapy utilizes high-energy ionizing radiation to damage the DNA of cancer cells, preventing them from dividing and growing. It can be delivered externally through machines that direct radiation from outside the body, known as teletherapy, or internally using sealed radioactive sources placed inside or near the tumour, a method called brachytherapy. In contrast, nuclear medicine employs unsealed radioactive drugs, or radiopharmaceuticals, which contain radioisotopes that emit particles such as beta, alpha, or Auger electrons. These drugs are highly targeted to cancer cells and are used for specific therapeutic purposes. Advancements in brachytherapy have paralleled those in external radiation therapy. Early methods involved low-dose rate (LDR) brachytherapy with radium-226 (^{226}Ra) and radon-222 (^{222}Ra) sources, which required several days of treatment and posed challenges related to radiation exposure and disposal. This led to the development of high-dose rate (HDR) brachytherapy using artificially produced radionuclides like Cobalt-60 (^{60}Co) and Iridium-192 (^{192}Ir). HDR brachytherapy significantly reduced treatment time from days to hours and introduced miniature sources and remote after-loading techniques, enhancing safety and efficiency. Today, radiation therapy has expanded beyond treating inoperable tumours. It has become the preferred treatment for cancers of the nasopharynx, anal canal, and cervix, often replacing surgery due to its effectiveness [3]. Targeted radionuclide therapies and theranostics are another avenue of advances in nuclear medicine. These therapies use radiopharmaceuticals that deliver therapeutic doses of radiation—alpha, beta, Auger, or conversion electrons—directly to diseased tissues. By targeting specific biological sites with molecular vectors, these treatments effectively induce cytotoxicity in tumor cells. Recent developments include the use of radionuclides like ^{131}I, ^{32}P, ^{166}Ho, ^{188}Re, ^{177}Lu, and ^{90}Y combined with receptor-targeting or immune-derived vectors to treat various cancers.

Advances have been fuelled by new isotopes produced at the Dhruva reactor at BARC and made available through the BRIT. This has expanded therapeutic options beyond traditional isotopes like ^{131}I and ^{32}P. Most notably, Lutetium-177 (^{177}Lu) has emerged as a key player in radionuclide therapy, providing a powerful alternative to radioiodine and significantly impacting cancer treatment in India. BARC has standardized the production of ^{177}Lu and developed several ^{177}Lu-based treatments, making them a cost-effective option for patients [4]. Additionally, BARC has innovated by sourcing Yttrium-90 (^{90}Y) from Strontium-90 (^{90}Sr) recovered from high-level liquid radioactive waste, demonstrating a successful recovery of valuable resources. The development of a ^{90}Sr-^{90}Y generator and ^{90}Y-based radiopharmaceuticals has advanced clinical cancer treatment options.

Radiation Safety in Healthcare: Safety is a key concern in both nuclear medicine and radiotherapy. For patients, risks are mitigated by precisely calculating radiation doses and employing advanced technologies to minimize exposure to healthy tissues. The principles of radiation protection—time, distance, and shielding—are applied to ensure that radiation exposure remains as low as reasonably achievable (ALARA). Caregivers are also safeguarded through various safety measures. They use shielding devices, maintain a safe distance from radiation sources, and limit their exposure time. Strict safety protocols and comprehensive training are implemented to protect both caregivers and patients from unnecessary radiation. Regulatory bodies such as the Atomic Energy Regulatory Board (AERB) and international organizations like the International Commission on Radiological Protection (ICRP) establish standards and limits to ensure safety from radiation hazards in medical settings. In addition to regulations, trained experts in medical physics and radiation safety are essential for ensuring safe radiation exposure in healthcare. The DAE supports this critical need by offering diploma in radiological physics and other radiation safety certification courses. Graduates of these programs become medical physicists in nuclear medicine centres, radiation safety officers at various facilities, and expert technicians in radiography instrumentation, among other health-care related employment opportunities.

Current State of Nuclear Medicine and Future Requirements: BRIT, a unit of the DAE, provides various products for nuclear medicine, including $^{99}Mo/^{99m}Tc$ generators, radioiodine, ^{177}Lu, ^{153}Sm, and cold kits for scintigraphy studies. Despite these efforts, there is an increasing reliance on imported supplies for $^{99}Mo/^{99m}Tc$ generators and certain therapeutic radiopharmaceuticals such as ^{177}Lu PSMA and 177Lu DOTATATE, which are used to treat prostate and neuroendocrine tumors [5]. Many major centers continue to depend on these imported resources. Additionally, $^{68}Ge/^{68}Ga$ generators, Thallium-201 (^{201}Tl), and alpha emitters are not produced domestically and are fully imported for PET and SPECT imaging and therapy. The demand for these isotopes is anticipated to rise significantly due to their growing use in cancer treatment.
In 2018, BARC enhanced its radioisotope production capabilities by upgrading the APSARA(U) reactor, which now produces key theranostic radioisotopes such as ^{64}Cu. Despite this, high costs and dependence on imported radioisotopes have hindered the advancement of alpha therapy in India. To address this issue, the DAE has proposed a new nuclear reactor for isotope production through a public-private partnership, aimed at advancing nuclear medicine and making radionuclide therapies more affordable for cancer patients [5]. Additionally, to address global shortages of ^{99}Mo affecting gamma imaging, India is developing a LINAC-based system to produce ^{99}Mo as an alternative. The BRIT has also set up a Fission Moly Plant to produce high-specific-activity ^{99}Mo domestically, thereby improving the country's self-reliance in nuclear medicine.

Over time, the leadership of the DAE in nuclear medicine has led to significant advancements in research on new radiopharmaceuticals and the establishment of a comprehensive network of diagnostic and therapeutic centers. Currently, India has 520 operational nuclear medicine centers, which include 24 medical cyclotrons, over 350 PET-CT scanners, 2 proton therapy machines, and more than 150 high-dose radionuclide therapy facilities. However, to address the needs of India's large population, these facilities will need to undergo further rapid expansion and enhanced in-house R&D. This effort includes advancements in equipment development and interdisciplinary research into AI-enabled theranostics, which combines therapy and diagnostics. With focused R&D and strategic planning, India is expected to achieve self-reliance in nuclear medicine by 2047, in line with the vision of Viksit Bharat.

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