IAEA
International Atomic Energy Agency

TRAINING COURSE SERIES

No. 88

Guidelines for the Harmonization of Education and Training Requirements in Radiopharmacy

GUIDELINES FOR THE HARMONIZATION OF EDUCATION AND TRAINING REQUIREMENTS IN RADIOPHARMACY

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS, THE
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CABO VERDE
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
COMOROS
CONGO
COOK ISLANDS
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GAMBIA, THE
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUINEA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS, KINGDOM OF THE
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT KITTS AND NEVIS
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAMOA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOMALIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TONGA
TRINIDAD AND TOBAGO
TUNISIA
TÜRKİYE
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

TRAINING COURSE SERIES No. 88

GUIDELINES FOR THE HARMONIZATION OF EDUCATION AND TRAINING REQUIREMENTS IN RADIOPHARMACY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2025

COPYRIGHT NOTICE

For further information on this publication, please contact:

Radiochemistry and Radiation Technology Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

GUIDELINES FOR THE HARMONIZATION OF EDUCATION AND TRAINING REQUIREMENTS IN RADIOPHARMACY
IAEA, VIENNA, 2025
IAEA-TCS-88
ISSN 1018-5518

Printed by the IAEA in Austria
June 2025
https://doi.org/10.61092/iaea.7uya-kb5t

FOREWORD

The radiopharmacy profession is an important component of nuclear medicine, which depends on the availability of safe and efficacious radiopharmaceutical products for patients. Radiopharmaceuticals are produced and used in different settings such as hospitals and centralized and industrial radiopharmacies. The IAEA has a long history of providing training in the safe operation of radiopharmacy facilities, especially to personnel from developing Member States. The IAEA publication Competency Based Hospital Radiopharmacy Training, published in 2010, covers the essentials of short training programmes for radiopharmacy practitioners, mainly for operation of level 1 and level 2 hospital radiopharmacy facilities. The use of radiopharmaceuticals has increased considerably over the past couple of decades for various nuclear medicine procedures and for both diagnostic and therapeutic purposes, and is expected to grow further in the coming years. However, many Member States are still lacking a formal radiopharmacy education programme that addresses the nuances and advances in the field.

These guidelines provide a useful reference for Member States interested in establishing a training programme to ensure good radiopharmacy practices where they do not yet exist, or to upgrade and improve existing programmes. This will help in mitigating the current heterogenicity among Member States in the education and training of radiopharmacists and provide guidance for authorization agencies in Member States to identify the competencies of qualified personnel for the production and release of radiopharmaceuticals for clinical use. This manual was prepared in consultation with experts from different regions through virtual consultancy meetings and is an outcome of the regional Latin America technical cooperation project on Strengthen the Regional Human Resource Development in Different Areas of Radiopharmacy.

The IAEA is grateful to all those who contributed to the development of this publication. The IAEA officer responsible for this publication was A. Korde of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

This publication has been prepared from the original material as submitted by the contributors and has not been edited by the editorial staff of the IAEA. The views expressed remain the responsibility of the contributors and do not necessarily reflect those of the IAEA or the governments of its Member States.

Guidance and recommendations provided here in relation to identified good practices represent expert opinion but are not made on the basis of a consensus of all Member States.

Neither the IAEA nor its Member States assume any responsibility for consequences which may arise from the use of this publication. This publication does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The authors are responsible for having obtained the necessary permission for the IAEA to reproduce, translate or use material from sources already protected by copyrights.

The IAEA has no responsibility for the persistence or accuracy of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The success of nuclear medicine for diagnostic and therapeutic applications depends largely on the quality of the radiopharmaceutical used. This is complicated by the inherent vulnerabilities and associated risks (both radiological and microbiological) of the intravenous administration route by which most radiopharmaceuticals (RP) are administered. Radiochemical purity of RP is of utmost importance, since this ensures that the radionuclide is not injected unbound in too large quantities. The free radionuclide can accumulate in off-target areas leading to poor quality diagnostic procedures or harmful side effects during therapy. The quality of RP, being free from undesired particles, endotoxins, and microbiological contamination is extremely important. Furthermore, they should also be proven to be non-toxic during the development phase of the radiopharmaceutical. Also, amongst other considerations, molar activity of the RP needs special attention, hence greater control on the quantity of the main carrier molecule (also called vector) is required. In such cases, more rigorous procedures of compounding and testing is needed. All the beforementioned considerations demand that an appropriately trained and qualified radiopharmacist is available to handle and manage the preparation and supply of RP doses for clinical use.

The field of RP is very dynamic and continually evolving. The emerging RP based on radionuclides that are newly applied to nuclear medicine, expand the number of useful tools for the screening and characterization of tissues [1-2]. The radiotherapeutics market is envisaged to double in the next decade. The success of these developments and their effective deployment for patients is linked to appropriately trained and educated human resources around the globe in this field [3].

It was identified very early that some of the most prevalent difficulties for the wider availability and access to safe and effective RP products would be the lack of human resources (capacity and capability) and knowledge gaps [4]. Currently there is a great lack of formal education in radiopharmacy in many MS [5]. Nevertheless, a great interest to initiate either training programmes, or postgraduate diploma and degree education, is seen presently. Furthermore, there is a need for specifying what training a person should undergo to be officially recognized as a competent radiopharmacist in the MS. In a recent publication focussing on the requirements presented in Africa, some global examples where also provided [6] and formal education, practical requirements and additional requirements vary widely from country to country. For example, South Africa requires a two-year master's degree qualification plus two years post-qualification experience, Belgium requires six-months training (after a master's in industrial pharmacy is obtained) with no additional post-training practical work and the United Kingdom requires a post-qualification diploma in radiopharmacy with no additional requirements [6-8].

This publication stating the minimum requirements for effective implementation of such programmes will not only be a useful orientation for educational institutes, but also bring awareness for enhancing the local government's commitments in the MS, recognition by regulatory bodies for accredited education and training programmes, and funding to support training and education in radiopharmacy.

1.2. OBJECTIVE

The main objective of this publication is to provide a standardised education and training programme for personnel to assure the adoption and implementation of good radiopharmacy

practices, essential for the medical applications as well as for the further growth of the RP sciences. This curriculum will provide a useful orientation for the MS and will help in reducing the current heterogenicity among radiopharmacists' education and training by setting a standard. The publication stating educational requirements for a competent radiopharmacist has been developed through consultation with experts from different MS covering different subject areas in radiopharmacy.

1.3. SCOPE

- Providing orientation for institutions in the MS that seek to strengthen existing, or implement new, education and training programmes in radiopharmacy;
- Providing orientation for regulatory bodies in MS to identify and/or specify which education and training should have been successfully completed for becoming a competent/certified radiopharmacist;
- Providing professional bodies guidance for the recognition of their members;
- Providing orientation to individuals serving, or aspiring to serve as, radiopharmacists in countries (often without formal education in radiopharmacy) on what knowledge and practical skills they should obtain to become a competent radiopharmacist and perform the full range of radiopharmacy practices.

1.4. STRUCTURE

In this publication, education refers to the formal university delivered degree programme whereas training is a short-term focused learning event that can be delivered by university, institutions including hospitals, centralized radiopharmacies or radiopharmacy industries possessing the required infrastructure and human resources.

Following this introductory section, Section 2 stipulates the education and training entry requirements for any person wanting to become a radiopharmacist. The goals of an education and training programme are outlined. Subsequently, the options on education and training methods are discussed, since the access to training in many of the MS might be limited. Section 3 provides details on how a new training programme can be implemented and lists the necessary infrastructure, knowledge, and personnel requirements.

The competencies in radiopharmacy required for radiopharmacists are outlined in Section 4 and the various competencies are linked to certain modules of the training programme as set out in Section 5. Some examples of practical experiences are briefly discussed in Section 6. Also, some assessment methods and criteria are proposed in Section 7. A bibliography for further reading is included.

2. GUIDELINES OF EDUCATION & TRAINING PRINCIPLES

Essentially, a radiopharmacist is a healthcare professional in charge of the responsibility for the preparation and quality control (QC) of RP used in nuclear medicine as diagnostic and/or therapeutic agents. Another useful definition is that by the IAEA Safety Standards Series No GSR Part 3 stating that a radiopharmacist is "a health professional, with specialist education and training in radiopharmacy, who is competent to prepare and dispense radiopharmaceuticals used for the purposes of medical diagnosis and radionuclide therapy (9). Although the number of RP products in use is much less compared to conventional non-radioactive pharmaceuticals, the majority of the RP are administered by the intravenous route, these and other non-injectable RP preparations also fall under the supervision of the radiopharmacist. Since a RP always incorporates at least one radionuclide, which is constantly decaying over time through the emission of radiation, it cannot be stored for long and should be prepared before use as dictated by the physical half-life of the radionuclide and the stability of the RP. When compared to other pharmaceuticals, the radiopharmaceutical's expiration date is normally short, from hours to days and seldom longer than a week. Quality control of produced RPs are therefore performed in a relatively rapid timeframe compared to traditional pharmaceuticals. A radiopharmacist is the professional possessing the scientific and technical expertise for accomplishing the preparation and QC of RP according to current good practices. Although this definition does not entirely cover the list of competencies that a radiopharmacist should possess (for an exhaustive list, refer to Section 4 on 'Competencies In Radiopharmacy'), it nevertheless allows to precisely identify the professional profile to which this education and training programme is addressed.

Qualified radiopharmacists require a minimum level of practical training in addition to formal academic education. There is a lack of formal academic programmes for the teaching of radiopharmacists and a lack of facilities covering all areas of radiopharmacy in many countries. Hence in addition to classroom training, there are different approaches or methods that can be used for the education and training of radiopharmacy specialists, such as a combination of e-learning and on the job training, exchange programmes and collaborative programmes of training, among others.

The characteristics, advantages and disadvantages of these methods are discussed in this section.

2.1. EDUCATION & TRAINING ENTRY REQUIREMENTS

Candidates to undertake an education programme in radiopharmacy, should possess a university degree in one or more of the following general disciplines: chemistry, pharmacy or biology or a related field. They should also preferably possess previous experience in the design and setting up of experiments in natural or health sciences and in the analysis of experimental data.

2.2. GOALS OF THE EDUCATION & TRAINING PROGRAMME

The scope of the education & training programme is to offer a general platform for ensuring that the qualified persons responsible for RP product release have the required competencies. This process typically includes further clarification of consolidated concepts, methods, techniques and operational procedures governing RPs and updating on the latest scientific, pharmaceutical, and technological advancements.

The training programme proposed here does not follow any singular specific learning approach, but it is inspired by the need for logical consistency and a rigorous analysis of the basic knowledge that should be an essential component of the radiopharmacist's background. These pedagogical constraints can ensure that the whole educational programme and specific sub-topics do appear sound and self-evident and, therefore, can be easily communicated and explained to the trainees.

2.2.1. E-learning

E-learning refers to all those education and training programmes that are carried out through electronic means, usually by using the internet. Teaching or training resources can include slides, videos, audio recordings, animations, graphics, or any other multimedia element that can be accessed online. An e-learning programme can be composed of short courses up to university master's level, which aim to update knowledge, skills, and abilities in highly specialized activities such as the ones performed in RP sciences. The IAEA has recently developed an e-learning programme in radiopharmacy as part of a technical cooperation project in radiopharmacy education for the African region and made it available to suitable universities in the region as a supporting programme for a master's degree in radiopharmacy.

2.2.2. On the job training

On the job training refers to training provided in the job workplace. It is a convenient hands-on method of teaching the skills, knowledge, and competencies needed to perform a special job in a real environment, by using the existing workplace tools, equipment, documents, and knowledge to teach the trainees. It is conducted and supervised by an experienced specialist or qualified radiopharmacist. Job shadowing is an effective form of on-the-job training, which consists of following and observing a well-trained and experienced co-worker. In some places, a residency programme in radiopharmacy is implemented, with the aim not only to train but to ensure the consistent availability of qualified radiopharmacists on site.

2.2.3. Exchange programmes

An exchange programme is a training scheme in which trainees from a given institution go to a partner institution to receive training. A training exchange programme does not necessarily require the trainee to travel abroad to receive training, it could be between partner institutions in the same country. Also, the term exchange does not necessarily imply to find a counterpart from the other institution with whom to exchange with. One of the characteristics that could be considered as an advantage of exchange programmes is that trainees expand their horizon by having the opportunity to visit and get training at other facilities. The receiving institution is usually a consolidated centre with the availability of all the required resources and experienced personnel capable of providing a comprehensive training.

2.2.4. Collaborative programmes

A collaborative programme refers to the training scheme offered by two or more institutions in partnership. Collaborative programmes are an efficient way to promote cooperative mechanisms to optimize and share resources, knowledge, and the expertise of partnership institutions.

Choosing the appropriate method for training radiopharmacy specialists will depend on several factors and will differ between institutions and countries. These factors include, but are not limited to, the number of people to be trained, the goals and objectives of training, the resources available such as personnel, physics and laboratory infrastructure and equipment. There is not a unique training method applicable to all institutions or countries, in fact it is necessary, and desirable, to combine different methods of training, as all of them have advantages and disadvantages as summarized in Table 1.

TABLE 1. ADVANTAGES AND DISADVANTAGES OF DIFFERENT TRAINING METHODS

Training method	Advantages	Disadvantages
E-learning	1) Flexibility and adaptability to the student or trainee's availability (time, place); 2) Savings in costs related to presential learning (e.g. travel and accommodation, living expenses); 3) Cost-effective method of education and training after the initial investment to develop the e-learning materials; 4) Almost no limit in enrolment capacity; 5) Possibility of personalized programmes according to defined educational or training objectives and educational background of the trainees; 6) Possibility of modules broken into segments with learning outcomes; 7) Compatibility with competency-based training; 8) Self-assessment during and at the end of the e-learning programme.	1) Reluctance of students or trainees to use new learning methods unfamiliar to them; 2) No direct interaction between trainer and trainees; 3) Inappropriate management of autonomy when not having an imposed work programme; 4) Time and resources needed to develop the e-learning materials and to keep them updated; 5) Lack of networking capacity and connections; 6) High dependence on connectivity may impact delivery of effective e-learning, given the known challenges in less developed countries; 7) Limited practical experience including hands-on training and lab work.
On the job training	1) It is easy to set up and can be implemented in a timely way; 2) Faster training with experience in a real job environment; 3) It is a training method that anybody can use; 4) Ability to see how different	1) Training is done only when there is time; 2) Training can interrupt the workflow and reduce the productivity of the trainer; 3) The methods taught by the trainer could be different than what is

TABLE 1. ADVANTAGES AND DISADVANTAGES OF DIFFERENT TRAINING METHODS

Training method	Advantages	Disadvantages
	operators perform procedures; 5) Training can be adjusted and customized based on the trainee's progress and specific role requirements.	written in the standard operating procedures; 4) The training can be unorganized and not done in a specific or established order; 5) The quality and completeness of training could be subject to the availability of resources, equipment, or trainer skills; 6) Can lead to an insufficient theoretical base needed to address/solve problems arising in the future professional practice.
Exchange programmes	1) Broadens the horizon of students and trainees by having the opportunity to visit other centres.	1) Availability of financial resources to cover travel and accommodation expenses; 2) Possible barrier of communication in exchange programmes between countries with different languages.
Collaborative programmes	1) Promotes cooperation between centres; 2) Efficient way to share resources knowledge and expertise; 3) Opportunity of complementary training between institutions dedicated to PET only and/or SPECT only radiopharmacies; 4) Assist in the fostering of professional connections and building professional networks.	1) Lack of institutions with similar level of development and/or expertise for effective collaboration in some countries.

3. PROGRAMME INFRASTRUCTURE REQUIREMENTS: FOR PRACTICAL TRAINING

Section 1 Introduction and the following four sub-sections (Background, Objective, Scope and Structure) are mandatory elements of IAEA publications.

3.1. FACILITIES

The facilities for the practical training of the radiopharmacist should meet high quality standards to enable state of the art training. Therefore, the following requirements should be in place:

- The facility should comply with national regulations and preferably be designed according to the principles and rules of Good Manufacturing Practice (GMP) so that the radiopharmacist in training can practice in an actual GMP environment. Access to full GMP facilities is usually limited for training purpose, alternatives such as simulation, or different virtual media could be used for initial introductions. This can include accreditation or certification according to the various local regulations by the relevant accrediting bodies to ensure that the facility meets the educational and operational standards;

- To properly perform such training, the preparation room should have sufficient space to allow students not to interfere with any ongoing dose preparation for patients. If such GMP compliant facilities are not available, alternative strategies should be pursued, such as visiting other institutes or simulation settings. Hospital based good radiopharmacy practice compliant facilities could also be considered;

- The facility should have authorization for operation in place (as required by their national nuclear energy regulations) to work with specific radionuclides. This is important to ensure that the practical component of the training can take place in the facility (or what other arrangements had been made) and not to have theoretical only training provided to participants. Therefore, there should be sufficient measures to work safely from the radiation protection point of view with respect to shielding, presence of hot cells, air ventilation and air filtering and radioactive waste management. Also, radiation monitors in the lab rooms should be in place to measure dose rates in the lab while performing a preparation. Furthermore, radiation waste disposal systems, personnel monitoring dosimeters such as TLDs, Personal protective equipment PPE and a decontamination facility should be available;

- Besides a GMP cleanroom, a separate lab for QC is preferred as performance of these tests does not require GMP cleanroom conditions.

For performing sterility tests of drug products and analysis of microbiological monitoring, access to appropriately equipped microbiology lab facilities is highly important.

3.2. EQUIPMENT

A variety of equipment should be available in, or accessible to, the facility to train all aspects of the competences needed for radiopharmacy training.

A cyclotron is vital to have access to short lived radionuclides for Positron Emission Tomography (PET) such as fluorine-18 (^{18}F) and carbon-11 (^{11}C) Longer lived radionuclides for PET, Single Photon Emission Computed Tomography (SPECT) diagnostic imaging and therapeutic radionuclides such as iodine-131 (^{131}I) and lutetium-177 (^{177}Lu) can be obtained from external sources.

Radionuclide generators producing gallium-68 (^{68}Ga) and technetium-99m (^{99m}Tc) should be in place to train with these very frequently used radionuclides.

Furthermore, the following equipment is required (but not limited to this list) for practical training covering the full spectrum of production and QC of RP:

- Synthesis modules;
- Laminar Air Flow unit;
- Dose calibrator;
- Sterile dispensing system;
- Radio thin layer chromatography (TLC) scanner;
- Autoradiography or phosphor imager;
- Gas liquid chromatograph (GC);
- Radio high performance liquid chromatography (HPLC) or ultra high-performance liquid chromatography (UHPLC);
- Particle counter;
- Gamma counter (scintillation detector or multichannel analyzer (MCA) with a high purity germanium detector (HPGe);
- Radiation monitors and other equipment to check personal contamination;
- Equipment for monitoring endotoxin contamination;
- Filter integrity testing equipment;
- Equipment for sterility testing of RP.

3.3. FACULTY

Regarding faculty, a competent radiopharmacist should be available at the facility, or close contact with a trained radiopharmacist should be facilitated to receive appropriate feedback, directions and have discussions on the progress of the training aspects. It is of utmost importance that experienced teachers in radiopharmacy, and nuclear medicine be available for teaching theoretical aspects.

It is worth to emphasizing the critical role played by the lecturer. Only lecturers having an unbiased scientific knowledge and a proved competency and experience in the science of RP, or in specific areas related to RP preparations, should be selected to teach multitude of subjects included in the educational programme. On site, there should be supporting staff for training that is responsible for daily supervision. In practice, this supporting staff can be the trained radiopharmacist him/herself or another trained professional like a radiochemist.

4. COMPETENCIES IN RADIOPHARMACY

Radiopharmacy involves the development, manufacturing, QC and dispensing of RP for diagnostic and therapeutic purposes. Most RPs are sterile, and pyrogen free solutions administered by intravenous injection, and so their preparation needs to be performed under aseptic conditions. The main responsibility of radiopharmacists is the preparation of RPs and to ensure their safety and quality. To accomplish that, radiopharmacists need to possess basic competencies. The tasks and responsibilities of radiopharmacists involve establishing and maintaining a radiopharmaceutical quality system as well as performing the activities of management, implementation, supervision, and ensuring regulatory compliance. As depicted by Fig. 1, the competencies are also critical for the radiopharmacist to participate in a multidisciplinary team of nuclear medicine specialists and contribute towards effective delivery of health care for the patient. To perform the tasks depicted here requires different competencies, on which this publication aims to provide guidance.

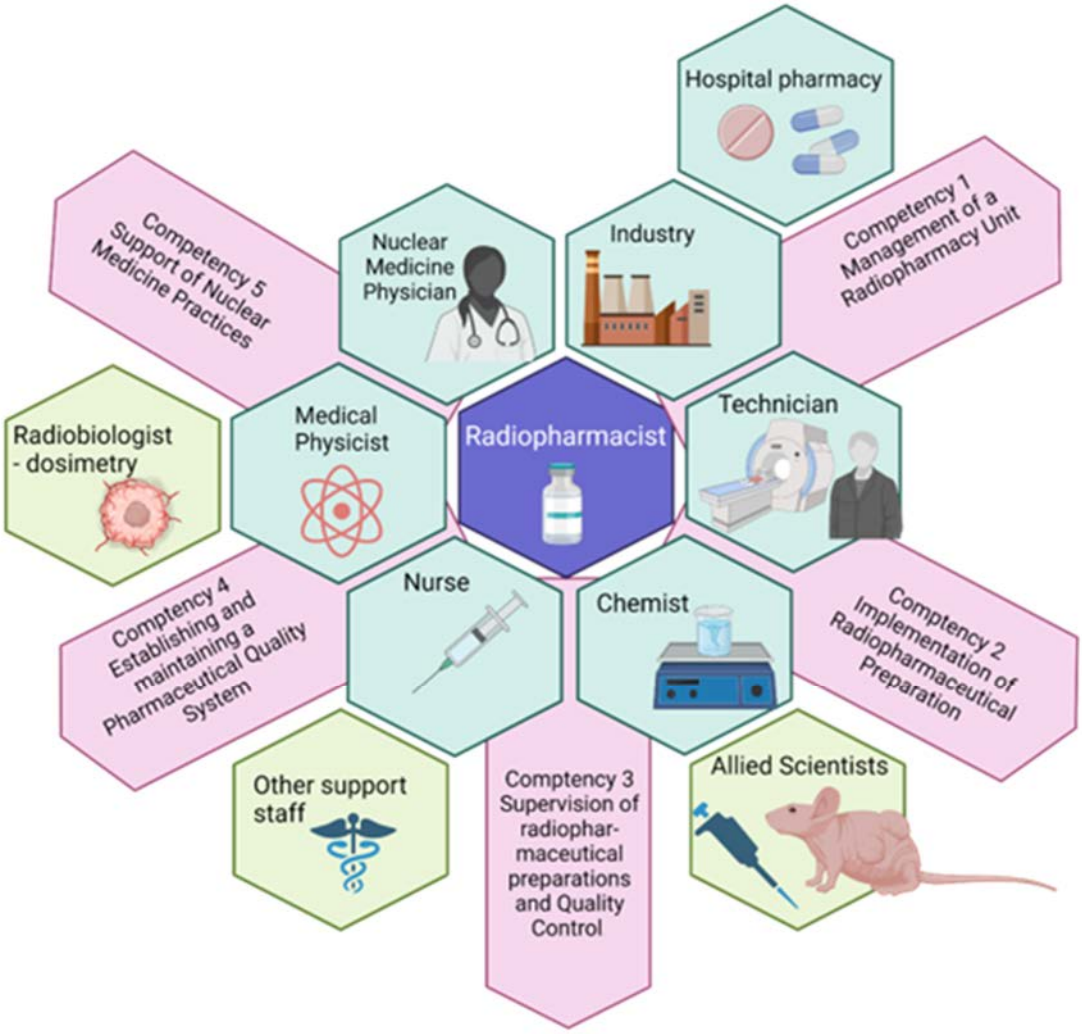

FIG. 1. The functioning of the radiopharmacist with different competencies as part of the multidisciplinary nuclear medicine team (Image courtesy of J. Kleynhans, Stellenbosch University).

Based on the multidisciplinary environment and the functioning of a radiopharmacist in this system, as depicted in Figure 1, a list of non-exhaustive or limitative list of competencies in radiopharmacy is provided in Table 2. These competencies are further outlined in modules listed in Section 5.

TABLE 2. COMPETENCY 1- MANAGEMENT OF A RADIOPHARMACY UNIT

1A	Designs radiopharmacy and defines user requirements for facility and equipment. This includes designing new radiopharmacies but also upgrading and maintaining the existing infrastructure. *Linked to modules 1.11, 7.1, 7.4 and 7.5.*
1B	Selects equipment for production and QC. *Linked to modules 1.4, 3.9, 4.4, 4.5, 4.9, 5.11 and 6.8.*
1C	Selects and orders RP and starting materials including considerations of legal status and requirements. *Linked to modules 7.1 and 7.19.*
1D	Controls incoming materials. *Linked to module 7.1.*
1E	Runs and maintains a documentation system for all radiopharmacy and related nuclear medicine procedures. *Linked to modules 7.2, 7.3, 7.6, 7.18, 7.19*
1F	Defines and ensures personnel resources for running the radiopharmacy. *Linked to module 7.7.*
1G	Ensures qualification of equipment and installations in the radiopharmacy. *Linked to modules 1.4, 7.5, and 7.15*
1H	Ensures periodic calibration, verification, and preventive maintenance of equipment. *Linked to modules 1.4, 1.5 and 7.15.*
1I	Establishes waste management and cleaning procedures. *Linked to modules 7.12 to 7.14.*
1J	Ensures regulatory compliance of packaging and shipments (incoming and outgoing). *Linked to modules 1.12 and 7.17.*
1K	Ensures monitoring of clean room facilities. *Linked to modules 7.13 to 7.14.*
1L	Defines radiation safety procedures and ensures required equipment and installations in cooperation with the medical physicist or radiation protection officer, to ensure compliance with radiation safety regulations. *Linked to modules 1.7 to 1.12.*

TABLE 3. COMPETENCY 2- IMPLEMENTATION OF RP PREPERATION

2A	Knows state of the art procedures of RP preparations and their QC and follows relevant novel developments and techniques. *Linked to modules 1.2, 1.13, 4.2, 4.3, 4.6 to 4.8 and 4.11, 5.2 to 5.6 and 5.14, 6.4 to 6.7. The whole of module 3 provides a basic background*.
2B	Defines personnel, equipment and materials for a specific radiopharmaceutical process. *Linked to modules 4.2 and 4.3, 5.2 to 5.10, 6.4 to 6.7 and 7.4 to 7.7.*
2C	Identifies risks depending on the type of process (e.g., kit based vs. automated module) and selects the method of choice considering legal, technical, and clinical requirements. *Linked to all of module 3, modules 5.10, 7.3 and 7.8.*
2D	Selects materials and their required controls and release procedures. *Linked to modules 4.4, 4.5 and 4.9, 5.11, 6.8 and 7.9.*
2E	Defines release criteria and, if applicable, specifications of the RP prepared. *Linked to modules 7.1, 7.2 and 7.9.*
2F	Prepares required documentation for a dedicated process and related QC (standard operating procedures batch records, forms). *Linked to module 7.6.*
2G	Ensures proper conduct of processes and validation of analytical methods. *Linked to module 7.9.*

TABLE 4. COMPETENCY 3- SUPERVISION OF RP PREPERATIONS AND QC

3A	Ensures appropriate training and responsibilities of technical staff including aseptic techniques. *Linked to modules 7.7, 7.8, 7.12, 7.13 and 7.14*
3B	Manage the control and release of starting materials including appropriate documentation. *Linked to modules 1.6, 4.2,4.3, 4.6, 4.7, 4.8, 5.2 to 5.10, 6.4 to 6.7, 7.8, 7.10 and 7.11.*
3C	Conducts or supervises the QC and release of RP prepared in the radiopharmacy. *Linked to modules 3.9, 4.4, 4.5, 4.9, 5.11, 6.8 and 7.9.*
3D	Ensures compliance of analytical methods with pharmacopeial standards including availability of standards. *Linked to modules 3.9, 4.4, 4.5, 4.9, 5.11, 6.8, 7.9, 7.15 and 7.19.*
3E	Performs QC's follow-up by means of trending, audit and improvement. *Linked to modules 7.2, 7.3 and 7.16.*
3F	Performs follow-up and troubleshooting of productions, investigate errors and ensures that appropriate corrective actions are taken to prevent their recurrence. *Linked modules 7.2. 7.3, 7.16 and 7.18.*
3G	Ensures continuous refresher education of personnel in all radiopharmacy related matters including her/himself. *Linked to all of modules 1 to 6. Especially linked to modules 4.13, 5.14, 6.13 and 7.19.*

TABLE 5. COMPETENCY 4- ESTABLISHING AND MAINTAINING A PHARMACEUTICAL QUALITY SYSTEM

4A	Knows valid regulations related to good manufacturing and pharmacy practices. *Linked to the whole of module 7.*
4B	Designs, implements, and manages a pharmaceutical's quality assurance programme including quality risk management. *Linked to module 7.3.*
4C	Defines qualification and validation requirements and implementing validation of procedures and methods. Linked to modules *7.1, 7.5, 7.6, 7.7, 7.8, 7.11, 7.13 and 7.15.*
4D	Ensures compliance of quality assurance system and validation status with current requirements including pharmacopoeia standards. *Linked to module 7.19.*
4E	Defines responsibilities for personnel, ensures that the radiopharmacist oversees release of RP preparations. *Linked to module 7.7.*
4F	Prepare for and manage internal and external audits. Implement changes based on audit findings to improve quality. *Linked to module 7.16.*

TABLE 6. COMPETENCY 5- SUPPORT OF NUCLEAR MEDICINE PRACTICES

5A	Providing orientation on the selection of radiopharmaceuticals. *Linked to all of modules 1 to 6.*
5B	Knows about availability and legal status of RP. *Linked to module 7.19.*
5C	Supports interpretation of clinical outcome related to the RP used. *Linked to modules 4.12, 5.13, 6.9, 6.11 and 6.13.*
5D	Advises on drug interactions with RP. *Linked to the whole of module 2.*
5E	Measures pharmacokinetic parameters (excretion, blood sample measurement and calculation). *Linked to modules 1.10, 1.15, 2.6 to 2.8, 4.10, 5.12, 6.9, 6.10 and 6.12.*
5F	Collaborate in the development and implementation of administration tools, e.g. for therapeutic RP. *Linked to module 2.9 and the whole of module 6.*
5G	Knowledge of specific radiopharmacy procedures and relevant pharmaceutical regulatory compliance measures in clinical trials. *Linked to modules 6.13, 7.1 and 7.19.*

Besides the competencies listed above, radiopharmacists require additional competencies and skills to successfully supervise and organize a radiopharmacy. These include social and managerial skills such as: communication skills; general staff management; conflict mediation; economics; time management; confidentiality with sensitive data e.g., patient related.

5. EDUCATION PROGRAMME TO ACHIEVE/ACQUIRE COMPETENCIES

To fulfil the competencies as described in the previous section, several teaching modules are envisioned that will assist in this task, which are detailed in Tables 2–8 below. The modules consist of 3 basic modules related to the physics and biology of radiation, biology and pharmacology, and chemistry. These are followed by specific teaching modules for different categories of RP, namely, for SPECT, PET and therapy. Finally, there is a dedicated teaching module for GMP.

TABLE 7. MODULE 1 – PHYSCIS AND BIOLOGY OF RADIATION

NO	SUBJECT	KEYWORDS
1.1	Physics of radioactive decay	Atomic and nuclear structure; radioactive decay; radioactive decay law; types of radioactive decay, table of nuclides, nomenclature, and classification of nuclides; half-life; decay constant.
1.2	Radiochemical equilibrium	Decay chains; Bateman equation: secular and transient equilibrium; basics of radionuclide generators.
1.3	Interaction of radiation with matter	Photoelectric effect, Compton scattering; pair production; attenuation coefficients; stopping power; charged particle ranges; linear energy transfer, bremsstrahlung, Cherenkov radiation, interaction of neutrons.
1.4	Detection and measurement of radiations	Gas filled detectors; solid state detectors (semiconductors); scintillation detection (liquid and solid); basic principles of SPECT and PET; detector characteristics (resolution, efficiency, sensitivity); calibration; background radiation.
1.5	Statistics applied to the measurement of radiation	Sources of error; statistical models; estimation of precision of a single measurement; error propagation; effects of background, limits of radioactivity measurements. Statistical distributions (Poisson distribution & Gaussian distribution); error types; measurement uncertainty; confidence intervals.
1.6	Gamma spectrometry	Selection of detector (solid state vs scintillators); electronic instrumentation; energy and efficiency calibration; identification and quantification of radionuclides.
1.7	Biological effects of radiations	Relative biological effectiveness; dose and dose rate effectiveness; age at exposure; internal and external exposure; stochastic effects; deterministic effects; direct and indirect cell damage; lethal, sublethal and potentially lethal damage; genetic effects; tissue reactions; DNA damage; cellular repair mechanisms; dose-response relationship; radiation-induced mutagenesis.
1.8	Radiation protection (recognize previous training according to local national regulations)	This should include (but not be limited to): Exposure situations; regulation of dose uptake and ICRP principles; quantities and units; external vs internal uptake; ALARA & ALARP; personal protective equipment, radiation exposure & occupational health management programme; regulatory framework; regulatory standards; risk assessment; risk management; radiation safety culture; prevention of accidents/incidents; incident reporting.
1.9	Internal Dosimetry	MIRD formalism; committed dose equivalent; committed effective dose equivalent; whole body counting; dosimetry models and calculations; measurement techniques (in vivo/ in vitro); dose coefficients; dosimetry software.

NO	SUBJECT	KEYWORDS
1.10	External dosimetry and shielding	Fluence, kerma, exposure; absorbed dose; equivalent dose; effective dose; radiation dose limits; external dose measurement devices; specific exposure rate constant; types of shielding.
1.11	Safety aspects of handling of radioactive material and waste management	Radioactive waste classification by the IAEA, biohazardous and medical radioactive waste; long lived and short lived radioactive waste; low and intermediate level radioactive waste; storage of radioactive waste; solid, liquid, and gaseous radioactive waste; radioactive waste disposal, dilute and disperse; delay and decay; concentrate and contain; international guidelines and national legislation; waste management strategies (minimization and segregation); contamination control; decontamination procedures; safe handling practices; environmental monitoring.
1.12	Transport of radioactive material	Regulatory framework and responsibility; transport safety; competent authority; consignor; carrier; consignee; materials classification and package types; emergency response; shipping of short-lived radionuclides, container types, ADR, IAEA regulations; labelling and documentation; transport index; radiation protection during transport; security measures.
1.13	Nuclear reactions and production of radionuclides	Q value, threshold energy; nomenclature of nuclear reactions; cross section; production rates (yield); nuclear fission and nuclear fusion, nuclear reactors, particle accelerators, principles of reactor, cyclotron and generator production of radionuclides; molar/ specific activity.
1.14	Numerical exercises of radioactive decay and use of nuclides' charts	Nuclear stability and magic numbers; valley of stability; nuclear drip line; isotopes; isotones; isobars; practical examples.
1.15	Practical aspects of detection and measurement of radiations	Geometry effects, dead time, auto absorption, counting efficiency, including practical examples.

TABLE 8. MODULE 2 – BASIC BIOLOGY AND PHARMACOLOGY

NO	SUBJECT	KEYWORDS
2.1	Structure and function of the cells, mechanisms of growth and death	Organelles and their function; cellular membranes; appearance of basic tissue types; apoptosis; necrosis; cell cycle; blood elements (red blood cells, white blood cells and platelets).
2.2	Basic pharmacokinetics and organ physiology	An introduction to ADME, normal function of organs; organ systems including (but not limited to): blood brain barrier function; homeostasis; perfusion and the cardiovascular system; respiratory system; reticuloendothelial system; neuroendocrine systems; central nervous system; musculoskeletal system; immune system; urinary system; gastrointestinal system.
2.3	Advanced pharmacokinetics and pharmacodynamics	Compartmental models; rate constant; examples of rapid and slow kinetics; quantification; protein binding; biological and physical half-life resulting in effective half-live; substrate specific distribution; substrate non-specific biodistribution; mean transit time.
2.4	Metabolism and excretion of RP	Glucuronidation; sulphonation; other general metabolic pathways; effect on excretion; hepatobiliary; renal excretion.
2.5	Chemistry of biomolecules: proteins, peptides, aptamers, nucleic acids, carbohydrates and fatty acids.	Chemical structures; amino acids; protein synthesis; DNA-synthesis; metabolic pathways; tertiary structure of proteins.
2.6	Uptake mechanisms and interaction of RP with cells, and tissues, membranes and receptors	Uptake mechanisms of RP, receptor types; agonist, antagonist; second messenger; G-protein coupled receptors; transport proteins, lipophilicity; non-specific binding; internalisation; receptor saturation.
2.7	Structure and function of the enzymes	Active site; prosthetic group; catalysis; enzyme kinetics, Michaelis Menten.
2.8	Antibodies and antibody constructs: structure and functions	Antigens, antibodies and engineered antibody constructs, kinetics, antigen binding site, affinity; biological half-live.
2.9	Basic biology of the cancer cell	Differences with normal cell; tumour immunology; T-cells; proliferation markers.

TABLE 9. MODULE 3 – BASIC CHEMISTRY

NO	SUBJECT	KEYWORDS
3.1	Chemical bond, functional groups	Electron configurations and the periodic table of elements; Lewis structures and the valence bond theory; Hund's rule; molecular geometries and hybrid orbitals; resonance and delocalized molecular orbitals; aromaticity; s and p bonding; examples of organic chemistry functional groups.
3.2	Polarity and electronegativity	Temporary dipole moment, electron density; polarizable bonds; molecular geometry and permanent dipole moments; hydrogen bond; weak interactions (London and Van der Waals).
3.3	Acid base equilibrium	Lewis acids and bases; Brönsted-Lowry acid-base theory, Ionic product of water (Kw); Dissociation constants and strength of acids and bases; pH and conjugated acids and bases; hydroxides; salts; hydrolysis; buffer solutions; hard and soft acids and bases.
3.4	Stereochemistry	Molecular geometries and spatial symmetries; Stereoisomerism and chirality: priority rules; absolute configuration; symmetry dependent biological interactions.
3.5	Substitution reactions (electrophilic and nucleophilic reactions)	Chemical reaction rates; order of a chemical reaction; reaction mechanisms; substitution and elimination reactions; nucleophilicity and electrophilicity; dependence of reaction rates from the stereochemistry of reacting molecules and the nature of the solvent; SN1, SN2, effect of structure, leaving group, nucleophile, solvent, stereochemistry.
3.6	Protecting groups	Electron donor and electron withdrawing substituents; role and chemical properties of protecting groups; mechanisms of hydrolysis; examples of reactions involving protecting groups.
3.7	Coordination chemistry	Electron configuration in metals, coordination bond, chelator, stability; metallic complexes; type of ligands; the chelation effect; s and p donors, and p acceptors; formation constants and stability; standard reduction potentials; oxidation states; symmetries and coordination geometries; inorganic functional groups; redox and ligand-exchange reactions.
3.8	Transition metals, metalloids, lanthanides, and actinides	S, p-block metals (metalloids); d-block metals (transition metals); f-block metals (lanthanides and actinides); the lanthanide contraction; oxidation states and aqueous stability.
3.9	Chromatography and analytics	Basic principles, stationary phase, mobile phase, partition coefficient, straight (normal) phase, reversed phase, TLC, HPLC, electrophoresis; gas chromatography; ultra-high performance liquid chromatography; detection methods and type of detectors, NMR, IR, mass spectroscopy, UV.

TABLE 10. MODULE 4 SPECT RP

NO	SUBJECTS	KEYWORDS
4.1	RP for SPECT	The characteristics of an ideal SPECT radiopharmaceutical; introduction to the design of a SPECT radiopharmaceutical; properties of SPECT radionuclides including (but not limited to) ^{111}In; ^{99m}Tc; ^{123}I, ^{67}Ga; ^{201}TI; ^{81m}Kr; ^{133}Xe.
4.2	Production of SPECT radionuclides	^{99}Mo / ^{99m}Tc generator production; generator components; generator elution; ^{99}Mo-breakthrough; nuclear fission; cyclotron production of radionuclides; world supply of ^{99m}Tc; reactor-produced γ-emitters; the ^{99}Mo/^{99m}Tc generator: theory and practice,
4.3	Preparation and molecular properties of ^{99m}Tc RP	The pertechnetate anion; the reduction of ^{99m}Tc pertechnetate; reducing agents; inorganic ^{99m}Tc functional groups (^{99m}Tc cores) and metallic fragments; production methods of ^{99m}Tc cores; s-donor and p-acceptor ligands; matching the ligand type with the ^{99m}Tc-core; symmetry and coordination geometries of ^{99m}Tc complexes; determination of the molecular structure of ^{99m}Tc; ligand exchange, function of kit ingredients.
4.4	Analytical methods used in QC of SPECT RP	Radio-HPLC; radio-ITLC; UPLC.
4.5	QC of ^{99m}Tc RP	Radiochemical purity including rapid testing methods and pharmacopoeia methods; radionuclidic purity and molybdenum breakthrough; sterility; bacterial endotoxin testing; sterility testing; aluminium breakthrough; specific and molar activity; radioactivity concentration; particulate testing; package integrity testing.
4.6	Production of kits for labelling with ^{99m}Tc	^{99m}Tc cold kit principles; ingredients; stannous chloride; aseptic production; freeze-dried kits; freeze-drying; sterilization methods including autoclaving and sterile filtration, QC of cold kits.
4.7	Labelling of biomolecules with ^{99m}Tc	Red blood cell labelling; leukocyte labelling; damaged red blood cell labelling; platelet labelling; pharmacophores, peptides, linkers and coordinating groups; bifunctional ligands; examples of conjugated ^{99m}Tc RP.
4.8	Preparation and molecular properties of ^{123}I and ^{131}I RPs	Radioiodination by electrophilic substitution; oxidizing agents; iododestannylation reactions; radioiodination by nucleophilic substitution; exchange radioiodination; radioiodination of proteins and peptides; direct radioiodination; prelabelled radio-iodinated prosthetic groups; stability of the iodine-carbon chemical bonds.
4.9	QC of iodine RP	Radiochemical purity; capsule dose filling; counting instruments.
4.10	Pharmacokinetics and pharmacodynamics of SPECT RP	Glomerular filtration rate determination; biodistribution & imaging time; lung ventilation (including ^{81m}Kr and Technegas); particulate imaging; pharmacological interventions; fatty meals during hepatobiliary imaging; the tracer principle; small-animal imaging.
4.11	Pitfalls in the use of SPECT RP	Problem solving of QC failures; quality assurance; RP quality factors affecting biodistribution; patient preparation; mis-injections; interaction of RP with patient´s medication.
4.12	Clinical applications of SPECT RP	Musculoskeletal system; neuroimaging; endocrine system; myocardial imaging; liver and reticuloendothelial system; lung imaging; renal imaging; oncology; neurology, cardiology nephrology and other diseases.
4.13	New advances in SPECT RP	Infection imaging; biomolecules and peptide-based RP; Molecular imaging; SPECT RP for selective targeting of disease-specific biomolecular substrates.

TABLE 11. MODULE 5 PET RP

NO	SUBJECT	KEYWORDS
5.1	RP for PET	The characteristics of an ideal PET radiopharmaceutical; an introduction to the design of a PET radiopharmaceutical; properties of common PET radionuclides including (but not limited to) ^{11}C; ^{18}F; ^{68}Ga.
5.2	Cyclotron: operating principle and systems	Schematic representation; D-shaped electrodes; magnet, RF system; vacuum system; ion source; extraction system; target.
5.3	PET radionuclides and characteristics	Conventional radionuclides (main sequence CNOF); nonconventional radionuclides (radiometals and radiohalogens).
5.4	Preparation and geometry of target irradiation	Gas targets; liquid targets; solid targets; solution targets for production of radiometals.
5.5	Techniques for radiochemical separation of targets	Ion exchange; dry distillation; solvent extraction; precipitation and filtration; electrochemical methods; thermal diffusion.
5.6	Generators to produce PET radionuclides	Working principle, examples for 68Ga and 82Rb; GMP compliant generators; generator eluate QC; generator maintenance and troubleshooting.
5.7	An introduction to the radiochemistry of non-metal PET radionuclides and specific radiolabelling methods	^{18}F: S_N2, S_NAr, late stage fluorinations, [^{18}F]AlF. ^{11}C; Chemistry for MeI and MeoTf, CO, methylation and carbonylation reactions; introduction to ^{15}O, and ^{13}N.
5.8	Radiochemistry of metallic PET radionuclides and radiolabelling methods	Procedures for ^{68}Ga, ^{64}Cu; ^{43,44}Sc; ^{89}Zr; ^{152}Tb; commonly used chelators; conjugation of chelator to targeting ligand; automated vs cold kits; PET amino acids; receptor targeting ligands (including peptide based).
5.9	Purification methods for PET RP	Distillation; solid phase extraction (SPE); preparative radio-HPLC; formulation.
5.10	Automation in the synthesis and dispensing of PET RP	Tubing based, and cassette based automated synthesis modules; semi-automated synthesis modules; overview of commercially available modules; GMP/Research; audit trail; good radiopharmacy practices automated synthesis in a hospital radiopharmacy.
5.11	QC of PET RP	Radiochemical purity (HPLC & ITLC), chemical purity; radionuclidic purity (identity); molar activity; pH; endotoxins, sterility; immunoreactivity; post-release; release criteria and certificate of analysis; gas chromatography; radioactivity measurement and instruments.
5.12	Biodistribution, pharmacokinetics and pharmacodynamics of PET RP	Examples of selected PET-RPs; suboptimal biodistribution (example – salivary glands & renal excretion); cardiovascular hibernation studies; paediatric dose calculation; SUV [^{18}F]FDG; hypoxia; pharmacological interventions.
5.13	Clinical applications of PET RP	Examples, practical aspect; translation of tracer to human use; patient preparation.
5.14	New developments in PET RP	Regulatory; (n)IMP; new tracers; total body PET; centralised production; other examples.

TABLE 12. MODULE 6 THERAPEUTIC RP

NO	SUBJECT	KEYWORDS
6.1	RP for therapy	Principles of radionuclide therapy: the characteristics of an ideal therapeutic radiopharmaceutical; an introduction to the design of a therapeutic radiopharmaceutical.
6.2	Nuclear properties of therapeutic RP	Beta minus emitters; alpha emitters and Auger emitters; linear energy transfer; theragnostic (or theragnostic) radionuclides; half-life; types of particulate emissions.
6.3	Safe handling of therapeutic radionuclides	Shielding, contamination, best practice; bremsstrahlung; volatility of ^{211}At and ^{131}I; application systems.
6.4	Production of therapeutic radionuclides	Cyclotron/reactor/ generator; workup; long lived contaminants; carrier added vs non-carrier added; molar activity; radionuclidic purity vs decay of short-lived impurities.
6.5	Labelling with radiometals	Typical chelators; the bifunctional approach; stability (including recoil energy principles and radiolysis); labelling conditions; purity of radiometal; molar activity; QC procedures.
6.6	Labelling with iodine	Iodogen method; hazards; nucleophilic substitution; oxidative methods; exchange methods.
6.7	Labelling and purification of peptides, antibodies, and antibody constructs	Conjugation methods for chelators; labelling conditions; Protein HPLC; size exclusion columns and cartridges; Formulation. Matching radionuclide with pharmacokinetics and patient tumour characteristics.
6.8	QC of therapeutic RP	Radiochemical purity (HPLC & ITLC), chemical purity; radionuclidic purity (half-live); pH; endotoxins, sterility; immunoreactivity; post-release; release criteria and certificate of analysis; special considerations for QC of radiopharmaceuticals based on alpha emitters.
6.9	Radiobiology applied to the use of therapeutic RP	DNA double-strand breakage; absorbed dose; 4R's of radiobiology; pharmacogenetics; pharmacogenomics; Biological effects of beta, alpha and Auger radiations; Cellular mechanisms of the therapeutic effect of radiation.
6.10	Internal dosimetry of therapeutic RP	Dosimetry; blood and marrow; dosimetry; radioiodine dosimetry; ^{177}Lu dosimetry and dosimetry for alpha emitters.
6.11	Pharmacokinetics and pharmacodynamics of therapeutic RP	Internalisation; recoil energy and radiolysis; kidney protection SSR targeting therapy; pharmacological interventions.
6.12	Clinical applications of therapeutic RP	Topics include (but are not limited to) relevant ongoing clinical trials; PSMA-radioligand therapy; peptide receptor radionuclide therapy, intraarterial treatment of liver cancer and liver metastases; benign thyroid disease; [^{131}I]MIBG; radioiodine therapy; radio-immunotherapy; radiosynovectomy; national and international guidelines for therapeutic applications of RP.
6.13	New advances in therapeutic RP	Examples e.g. RP based on ^{188}Re, ^{161}Tb, ^{177}Lu, TAT agents based on, ^{211}At; ^{225}Ac, $^{203/212}$Pb and other emerging alpha emitters; ^{64}Cu; auger emitters; nanoparticles etc.

TABLE 13. MODULE 7 – GOOD MANUFACTURING PRACTICES

NO	SUBJECT	KEYWORDS
7.1	Introduction to GMP	Meta searching of multiple content resources using the searcher's preferred query vocabulary
7.2	Quality assurance system	Indexing of content in a domain using the controlled vocabulary from another domain
7.3	Quality risk management principles	Linking of two or more databases that have been indexed using different controlled vocabularies
7.4	Design of the facilities	Linking of two or more controlled vocabularies to form a new controlled vocabulary that will encompass all the concepts and labels contained in the originals
7.5	Equipment	Multiple language searching, indexing, and retrieval
7.6	Documentation	Documentation management system; version control; record keeping ; SOPs; forms; records; making corrections.
7.7	Personnel	Minimum number; responsibilities; qualified person; head of production; head of QC; training and qualification records.
7.8	Production	Cross-contamination (line-clearance); audit trail; batch records; deviation handling; PQ procedure; labelling; bioburden test; validation of new/modified methods.
7.9	QC	Validation of methods; pharmacopoeia; acceptance criteria, data integrity.
7.10	Consumables and raw materials	Testing; quarantine; storage conditions; shelf-life.
7.11	Supplier qualification	Audit methods; criteria.
7.12	Cleaning and disinfection	Procedures; validation; closed and open systems.
7.13	Microbiological control	Clothing; air handling; cleaning (above). in combination with monitoring: settle plates; sedimentation plates; contact plates; media fill.
7.14	Monitoring	Check for bacterial strains; particle counting.
7.15	Validation of equipment	User requirements specifications; installation qualification; operational qualification; performance qualification; equipment maintenance and replacement plan.
7.16	Audit	External audit; self-inspection; follow-up actions; supplier audits.
7.17	Good Distribution Practices	GDP, documentation of shipment, storage and transportation requirements, temperature control, responsibilities.
7.18	Pharmacovigilance	Concept; examples; documentation; procedures of adverse event reporting; common side effects of RP; pharmacovigilance with therapeutic RP (including hormonal crisis during net treatment); misadministration.
7.19	Regulatory requirements for RP	Investigational medical dossier; orphan drugs; registration, compassionate use; pharmacopoeia monographs; good clinical practice.

6. PRACTICAL EXPERIENCE

The radiopharmacist practicing in a radiopharmacy should adhere to the applicable local regulations of the country/region. In some countries this might include (but not limited to) registration as a radiation worker and/or pharmacist or radiopharmacist.

Besides the required formal academic education, it is suggested that a minimum level of practical training should be also attained, under the conditions stated in Section 3 of this publication.

Table 9 contains the competencies that need to be possessed for the different radiopharmacy operation levels described in the IAEA publication 'Operational guidance on Hospital radiopharmacy' and the IAEA training course series publication 39. It is important to consider that the levels of associated risks in radiopharmacy increase with every level (refer to table 9) and hence practical training becomes even more important.

It is also important to note that regulatory authorities might request proof of practical experience. Logbooks and final reports from training providers are therefore important evidence that should be kept up to date with regards to efforts towards continuous professional development strategies.

It is accepted that the trainee learns basic practical skills that are necessary in any laboratory environment. This should be learnt before more advanced practical procedures are attempted. The range of skills includes (but is not limited to) the use of micropipettes, working in aseptic environments, weighing raw materials precisely, planning practical workflows, sourcing raw materials of suitable quality, performing basic chemical synthesis, performing chromatography, using syringes and needles, working with radioactivity and biohazardous materials like blood products and performing precise dilutions of fluids.

The detailed information given in Table 9 is based on radiopharmacy operation levels described in the IAEA publication 'Operational guidance on Hospital radiopharmacy' and the IAEA training course series publication 39.

TABLE 14. PRACTICAL TRAINING BASED ON OPERATIONAL LEVELS OF RADIOPHARMACY

OPERATIONAL LEVEL	OPERATIONS	PRACTICAL TRAINING
1A: Ready to use RP	Dispensing RP purchased in their final form from authorised manufacturers or centralised radiopharmacies.	Dose dispensing, dose calibration, dose labelling, radiation safety, aseptic procedures, record keeping, maintenance of a dose calibrator. Note that although Level 1 radiopharmacy does not use all the principles in the training programme; to be practicing as a radiopharmacist, you should have all the competencies to become a radiopharmacist.
1B: Radioiodine dispensing	Dispensing radioiodine (^{131}I) and other ready to use RP for radionuclide therapy.	Use and maintenance of fume hood, handling of b emitting radioisotopes, radiation safety, avoidance of contamination, managing inhalation risks of ^{131}I.
2A: Kits and generators	Preparation of RP from pre-prepared and approved reagent kits and radionuclides.	Closed procedures, use of generator systems (incl. maintenance), measurement of parent breakthrough in eluate, radiolabelling of cold kits, unit dose dispensing from multi-dose vials, QC, aseptic procedures, stock control, microbiological monitoring processes, radiation monitoring.
2B: Radiolabelled autologous products	Radiolabelling of autologous blood cells (red blood cells and white blood cells).	Aseptic technique, handling biological materials, operator safety, centrifuge, microscopy, cleaning biohazard and radiation hazardous material and waste handling.
3A: Compounding	In-house production of kits and other forms of compounding.	Principles of Good Radiopharmacy practices in the hospital/centralized radiopharmacy, microbiology aspects and aseptic techniques, licencing and regulations, freeze drying, building quality in the product, cold kit design and manufacturing.
3B: Preparation of radiolabelled therapeutics	Compounding of therapeutic RP.	Radiolabelling with therapeutic isotopes, radionuclidic purity, microbiological monitoring, all QC procedures and unique constraints, quality assurance, radiation protection, stability aspects, shipping and supply chain of therapeutic RP, unique constraints with alpha emitters, unique constraints with beta-emitters.
3C: Preparation of PET radiopharmaceuticals	Compounding of PET RP	An extensive training required at a cyclotron radiopharmacy and a radiopharmacy producing generator-based PET RP. This includes raw material management, production, QC and quality assurance. Training also needs to be done on automated synthesis modules.

7. ASSESSMENT METHODS AND CRITERIA

Completion of the education and training programme can be achieved in different ways or by means of the combination of learning strategies:

- Dedicated university courses;
- Established and dedicated online training courses (e-learning);
- Continuing education programmes e.g., at scientific meetings;
- Dedicated professional courses (e.g., GMP training programmes);
- Internship under supervision of a qualified radiopharmacist.

Assessment methods that are commonly applied during courses are traditional written exams, oral exams, direct observation and portfolios of evidence. Since a competent radiopharmacist should have both a broad knowledge of the theory as well as a high level of practical expertise, the optimal method should ultimately cover all these assessment methods.

Traditional written exams are very easy to standardize and allow for a fair comparison amongst candidates. However, traditional written exams are limited in translatability to real world cases and cannot adequately evaluate the candidate's scientific reasoning and problem-solving ability of the radiopharmacist during day-to-day practice, for which conducting additional unbiased oral examinations is helpful. For assessment of practical skills in the radiopharmacy, both direct observation and the evaluation of portfolios of evidence are critical methods of evaluation.

Direct observation is a very authentic assessment that allows for the evaluation of the candidate's skills in the radiopharmacy in a real-world setting. Since it also allows for the provision of immediate feedback to the candidate, this should not only be restricted to end-of-qualification assessment but should rather form part of a continuous assessment. Direct observation evaluation techniques might however be hampered by being resource intensive and having standardization challenges. The standardization of direct observation techniques could be alleviated by having a standardized observation form with prescribed procedures to be evaluated that have clear criteria. Clear criteria should be specific, measurable, achievable, relevant and time bound. Examiners should also be trained on the process of assessment and observation. The burden on resources might be alleviated by incorporating evaluations in the day-to-day practice of a radiopharmacy, should this not influence with the quality and timeliness of service delivery to patients.

Finally, portfolios of evidence are a very comprehensive form of assessment, and it allows the candidate to actively engage in self-reflection and self-assessment as they compile their portfolios. Portfolios also allow for the tracking of progress and development over time and enables longitudinal assessment.

A combination of multiple methods, tailored to the competencies required of a radiopharmacist will ultimately provide the most comprehensive and accurate evaluation of knowledge, skills and acquired competencies.

The assessment of completion can be based on respective certificates or certifications from universities or professional course organizers. All certifications should include content and credit hours. University certificates should include the level of education and be at master's level or equivalent. In case of non-university courses, appropriate quality certification of the course organizers should be provided. In case such certification is not available, the level and appropriate content of the course should be verified in the written form by a local expert

indicating the equivalence of the teaching content to the training programme outline. This can also be performed by responsible national regulatory authorities. In case of uncertainty and limited availability of evaluation experts, the IAEA can be asked to provide support to review the fulfilment of the training programme.

Normally, above the certification by the university or professional course organizer, additional processes are required to be officially recognised as competent in the country of practice. This could be required by one or more of the following authorizing agencies in the country such as the radiation control, the drug/pharmaceutical control agencies, or the health professional's council. It is highly important that whichever authority or authorities takes on the role of recognition of the radiopharmacist profession, should provide a clear set of competency standards and requirements against which the candidates will be evaluated to be declared competent. Final registration could be based on the provision of an approved training course/degree, required hours of internship, a portfolio of evidence and/or a written exam.

8. CONCLUSIONS

Details on the appropriate education and training required for the radiopharmacist are provided in this publication. A list of the required competencies is also provided. After completing all the suggested competencies as listed in this publication, the post-graduate trainee should be able to perform all the tasks falling within the scope of practice of a radiopharmacist. With this publication, the IAEA aims to provide support for the official recognition of the training required for competent radiopharmacists in MS, without prejudice to any existing practices or regulations in MS. This publication is useful for the planning of future radiopharmacy education and training activities under regional or national technical cooperation projects.

REFERENCES

[1] GEE, A.D., HERTH, M.M., JAMES, M.L., et al., Radionuclide Imaging for Neuroscience: Current opinion and future directions, Molecular Imaging. **19** (2020) 1. DOI:10.1177/1536012120936397.

[2] BODEI, L., HERRMANN, K., SCHÖDER, H., SCOTT, A.M., LEWIS, J.S. Radiotheranostics in oncology: current challenges and emerging opportunities. Nat Rev Clin Oncol. **19** (2022) 534. 10.1038/s41571-022-00652-y.

[3] GEE, A.D., ANDERSSON, J., BHALLA, R., et al., Training the next generation of radiopharmaceutical scientists. Nucl. Med. Biol. **88** (2020) 10. 10.1016/j.nucmedbio.2020.06.004.

[4] DUATTI, A., BHONSLE, U. Strengthening radiopharmacy practice in IAEA member states. Sem. Nucl. Med. **43** (2013) 118-194. 10.1053/j.semnuclmed.2012.11.009.

[5] EKOUME, F.P., RUBOW, S.M., ELREFAEI, A., BENTALEB, N., KORDE, A., SUMMERS, B., BOUYOUCEF, S., RADCHENKO, V., VRAKA, C., PICHLER, V. Radiopharmacy in Africa: current status and future directions. Nucl. Med. Biol. **114-115** (2022) 29-33. 10.1016/j.nucmedbio.2022.08.002.

[6] KLEYNHANS, J., SUMMERS, B., SAKR,, J. ZEEVAART JR., LUNDIE, J., DU PLESSIS, S., MOSIMA, L., BENTALEB, N., EKOUME, F.P., HLONGWA, K., SHAMBEL, S., MDLOPHANE A,., MANGATHA, A., MORE, S., Spotlight: the status of radiopharmacy in Africa. Clin Trans Imag. **12** (2024) 113-118. 10.1007/s40336-023-00594-0.

[7] FEDERAAL AGENTSCHAP VOOR NUCLEAIRE CONTROLE (2023) Radiofarmacie. [Date accessed 07/08/2024]. https://fanc.fgov.be/nl/professionelen/medische-professionelen/radiofarmacie

[8] BRITISH NUCLEAR MEDICINE SOCIETY (2013) What does a Radiopharmacist do? Working in nuclear medicine. [Date accessed 07/08/2024] https://www.bnms.org.uk/page/WhatdoesaRadiopharmacistdo

[9] Radiation protection and safety of radiation sources: international basic safety standards. IAEA-Safety Standards, IAEA, PART 3 Vienna (2014): 978-92-0-135310-8

BIBLIOGRAPHY

COENEN, H.H., GEE, A.D., ADAM, M., et al., Status of the Consensus Nomenclature Rules in Radiopharmaceutical Sciences Initiative, Nucl. Med. Biol. **71** (2019) 19.

EUROPEAN ASSOCIATION OF NUCLEAR MEDICINE, Radiopharmacy Certification (2020), https://www.eanm.org/esmit/radiopharmacy-certification/.

EUROPEAN MEDICINES AGENCY Radiopharmaceuticals - Scientific guideline (2018), https://www.ema.europa.eu/en/radiopharmaceuticals-scientific-guideline/.

INTERNATIONAL ATOMIC ENERGY AGENCY (Vienna)
Manual for reactor produced radioisotopes, IAEA-TECDOC-1340, (2003). 92-0-101103-2.
Operational Guidance on Hospital Radiopharmacy, A Safe and Effective Approach, STI/PUB/1342, Vienna (2008). 978-92-0-106708-1.

Cyclotron produced radionuclides: physical characteristics and production methods, Technical Reports Series 468, IAEA, Vienna (2009). 978-92-0-106908-5.
Competency Based Hospital Radiopharmacy Training, Training Course Series 39, Vienna (2010).

Planning a Clinical PET Centre, IAEA Human Health Series No. 11, IAEA, Vienna (2010). 978-92-0-104610-9.

Good practice for introducing radiopharmaceuticals for clinical use, IAEA-TECDOC-1782, IAEA, Vienna (2015). 978-92-0-111215-6.

Quality control in the production of radiopharmaceuticals, IAEA-TECDOC-1856, IAEA, Vienna (2018). 978-92-0-107918-3.

Production and quality control of fluorine-18 labelled radiopharmaceuticals, IAEA-TECDOC-1968, IAEA, Vienna (2021). 978-92-0-122721-8.

Alternative Radionuclide Production with a Cyclotron, IAEA Radioisotopes and Radiopharmaceuticals Reports No. 4, IAEA, Vienna (2021). 978-92-0-103021-4.

Guidance for Preclinical Studies with Radiopharmaceuticals, IAEA Radioisotopes and Radiopharmaceuticals Series No. 8, IAEA, Vienna (2023). 978-92-0-139322-7.

Pain Palliation of Bone Metastases: Production, Quality Control and Dosimetry of Radiopharmaceuticals, IAEA Radioisotopes and Radiopharmaceuticals Series No. 9, IAEA, Vienna (2023). 978-92-0-150022-9.

KOWALSKY, R., WEATHERMAN, K., Radiopharmaceuticals in Nuclear Pharmacy and Nuclear Medicine, 4th edn, APhA, Washington (2020). https://doi.org/10.21019/9781582122830.

KILBOURN, M., SCOTT, J., Handbook of Radiopharmaceuticals: Methodology and Applications, 2nd edn, Willey, New Jersey (2021).

LEWIS, J., WINDHORST, A., ZEGLIS, B., Radiopharmaceutical Chemistry, Springer, Cham (2019). https://doi.org/10.1007/978-3-319-98947-1.

METTLER, F., GUIBERTEAU, F., Essentials of Nuclear Medicine and Molecular Imaging, 7th edn, Elsevier, Philadelphia (2019). https://doi.org/10.1016/C2016-0-00043-8.

THEOBALD, T., Sampson's Textbook of Radiopharmacy, 4th edn, Pharmaceutical Press, London (2011).

SAHA, GB., Fundamentals of Nuclear Medicine, 7th edn, Springer International Publishing, Cleveland (2018).

U.S. FOOD AND DRUG ADMINISTRATION, PET Drug Products - Current Good Manufacturing Practice (CGMP) (2009), https://www.fda.gov/regulatory-information/search-fda-guidance-documents/pet-drug-products-current-good-manufacturing-practice-cgmp.

WORLD HEALTH ORGANIZATION, Annex 2: International Atomic Energy Agency and World Health Organization guideline on good manufacturing practices for radiopharmaceutical products, Technical Report Series No.1025, WHO, Geneva (2020) 93.

WORLD HEALTH ORGANIZATION, Annex 3: IAEA/WHO guideline on good manufacturing practices for investigational, Technical Report Series No. 1044, WHO, Geneva (2022).

LIST OF ABBREVIATIONS

[^{18}F]AlF	aluminium-[^{18}F]fluoride
^{111}In	Indium-111
^{11}C	Carbon-11
^{123}I	Iodine-123
^{131}I	Iodine-131
^{133}Xe	Xenon-133
^{13}N	Nitrogen-13
^{152}Tb	Terbium-152
^{15}O	Oxygen-15
^{161}Tb	Terbium-161
^{177}Lu	Lutetium-177
^{188}Re	Rhenium-188
^{18}F	Fluorine-18
^{201}Tl	Thallium-201
^{203}Pb	Lead-203
^{211}At	Astatine-211
^{212}Pb	Lead-212
^{225}Ac	Actinium-225
^{43}Sc	Scandium-43
^{44}Sc	Scandium-44
^{67}Ga	Gallium-67
^{68}Ga	Gallium-68
^{81m}Kr	Krypton-81m
^{82}Rb	Rubedium-82
^{89}Zr	Zirconium-89
^{99}Mo	Molybdenum-90

^{99m}Tc	Technetium-99m
ADME	Absorption, distribution, metabolism and excretion
ADR	Adverse Drug Reaction
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
DNA	Deoxyribonucleic Acid
GC	Gas Chromatography
GMP	Good Manufacturing Practices
HPGe	High Purity Germanium
HPLC	High Performance Liquid Chromatography
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IMP	Investigational medicinal products
IR	Infrared Spectroscopy
LAF	Laminar Air Flow
MCA	Multichannel analyser
MIBG	Meta-iodobenzylguanidine
MS	Member States
NMR	Nuclear Magnetic Resonance
PET	Positron Emission Tomography
PPE	Personal protective equipment
PSMA	Prostate Specific Membrane Antigen
QC	Quality Control
RP	Radiopharmaceuticals
S_N1	Substitution nucleophilic unimolecular
S_N2	Substitution nucleophilic bimolecular
SOP	Standard Operating Procedure

SPE	Solid Phase Extraction
SPECT	Single Photon Emission Computed Tomography
SSR	Somatostatin Receptor
SUV	Standardized uptake value
TAT	Targeted Alpha Therapy
TLC	Thin Layer Chromatography
TLD	Thermoluminescent dosimeter
UHPLC	Ultra-High Performance Liquid Chromatography
UV	Ultraviolet

CONTRIBUTORS TO DRAFTING AND REVIEW

Avila-Rodriguez M.	Research Division, Universidad Nacional Autónoma de México
Decristoforo, C.	Nuclear Medicine, Medizinische Universität Innsbruck, Austria
Duatti, A.	Chemical and Pharmaceutical Sciences University of Ferrara, Italy
Elsinga, P.H.	University Medical Centre Groningen, Netherlands
Kleynhans, J.	Division of Nuclear Medicine, Stellenbosch University, South Africa
Korde, A.	International Atomic Energy Agency, Austria
Rey Ríos, A.	Facultad de Química, Universidad de la República, Uruguay
Ramamoorthy, N.	Atomic Energy Regulatory Board, India

IAEA
International Atomic Energy Agency

CONTACT IAEA PUBLISHING

Feedback on IAEA publications may be given via the on-line form available at:
www.iaea.org/publications/feedback

This form may also be used to report safety issues or environmental queries concerning IAEA publications.

Alternatively, contact IAEA Publishing:

Publishing Section
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530
Email: sales.publications@iaea.org
www.iaea.org/publications

Priced and unpriced IAEA publications may be ordered directly from the IAEA.

ORDERING LOCALLY

Priced IAEA publications may be purchased from regional distributors and from major local booksellers.

25-01367E