

Nuclear medicine – towards universally accessible personalized health management

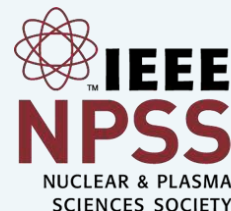
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Workshop on Nuclear Energy and Applications

October 19, 2026



What is nuclear medicine?

Specialty that uses **radioactively tagged**, biologically relevant **radiopharmaceuticals** for **imaging** or **treatment** purposes.



Radiopharmaceuticals

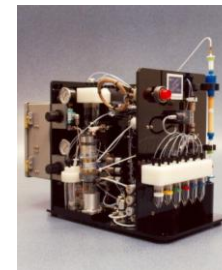
Radionuclide (γ , β^+ , β^- , α)

- Cyclotrons
- Generators
- Nuclear reactors



Biology + Radiochemistry

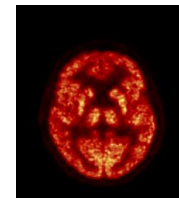
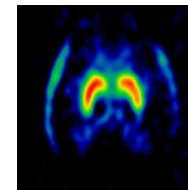
- +
- Determination of a biologically relevant target and radiolabeling of corresponding compound



Imaging: radiation detection + image reconstruction and quantification



Examples:



^{18}F -fluorodeoxyglucose (FDG) ^{18}F -fluorodopa(Fdopa)

Imaging (diagnostics and research):

Imaging techniques (gamma detection)

- Single Photon Emission Computerized Tomography (**SPECT** - single gamma detection)
- Positron emission tomography (**PET** - detection of 2 gammas in coincidence)

Requirements

- Low radioactivity dose
- High target specificity

Imaging and treatment: theranostics

Pairing two radiopharmaceuticals that target the same cellular marker in the body: one to see the target (imaging) and one to destroy the target (therapy)

Treatment (cancer)

- High radioactivity dose
- High target specificity

Example of pairs:

Prostate cancer (PSMA):

$^{68}\text{Ga}/^{177}\text{Lu}$

$^{68}\text{Ga}/^{225}\text{Ac}$

$^{64}\text{Cu}/^{212}\text{Pb}$

Applications



Imaging (diagnosis and research)

- Oncology
- Cardiology
- Neurology
- Endocrinology
- Bone scans
- Renal and gastrointestinal scans

Radioisotope selection criteria

- Emission type and characteristics
- Half life
- Easy to embed in a biologically relevant target

Treatment

Cancers (Targeted alpha therapy – TAT)

Thyroid disease

Nuclear medicine procedures

~**20 M** nuclear medicine procedure
are performed in the United States

~**10 M** in Europe

~ **15-20 M** in the rest of the world

~ 90% are diagnostic

*(Radioisotope in Medicine, World
Nuclear Association Oct 2026)*

Reactor produced radionuclides

Radioisotope	Half-life	Medical use / notes
Bismuth-213	46 min	Used for targeted alpha therapy (TAT), especially cancers, as it has a high energy (8.4 MeV).
Caesium-131	9.7 d	Used for brachytherapy, emits soft X-rays.
Cobalt-60	5.27 yr	Formerly used for external beam radiotherapy, now almost universally used for sterilising. High-specific-activity Co-60 is used for brain cancer treatment.
Iodine-125	60 d	Used in cancer brachytherapy (prostate and brain), also diagnostically to evaluate the filtration rate of kidneys and to diagnose deep vein thrombosis in the leg. It is also widely used in radioimmuno-assays to show the presence of hormones in tiny quantities.
Iodine-131	8 d	Widely used in treating thyroid cancer and in imaging the thyroid; also in diagnosis of abnormal liver function, renal (kidney) blood flow, and urinary tract obstruction. A strong gamma emitter, but used for beta therapy.
Iron-59	46 d	Used in studies of iron metabolism in the spleen.
Lead-212	10.6 h	Used in TAT for cancers or alpha radioimmunotherapy, with decay products Bi-212 (1 h) and Po-212 delivering the alpha particles. Used especially for melanoma, breast cancer and ovarian cancer. Demand is increasing. Used in cancer therapy.
Lutetium-177	6.7 d	Lu-177 is increasingly important as it emits just enough gamma for imaging while the beta radiation does the therapy on small (eg endocrine) tumours.
Molybdenum-99	66h	Used as the 'parent' in a generator to produce technetium-99m.
Palladium-103	17 d	Used to make brachytherapy permanent implant seeds for early stage prostate cancer. Emits soft x-rays.
Potassium-42	12 h	Used for the determination of exchangeable potassium in coronary blood flow.
Radium-223	11.4 d	Used for TAT of prostate cancer that has spread to bone, where it lodges. Alpha emitter.
Rhenium-186	3.8 d	Used for pain relief in bone cancer. Beta emitter with weak gamma for imaging.
Rhenium-188	17 h	Used to beta irradiate coronary arteries from an angioplasty balloon.
Samarium-153	47 h	Sm-153 is very effective in relieving the pain of secondary cancers lodged in the bone, sold as Quadramet. Also very effective for prostate and breast cancer.
Scandium-47	4.5 d	Sc-47 has similar properties to Lu-177 and may be used for therapy or diagnosis. It is produced by irradiating calcium-46 to produce Ca-47 which decays to Sc-47.
Selenium-75	120 d	Used in the form of seleno-methionine to study the production of digestive enzymes.
Strontium-89	50 d	Very effective in reducing the pain of prostate and bone cancer. Beta emitter.
Technetium-99m	6 h	Used to image the skeleton and heart muscle in particular, but also for brain, thyroid, lungs (perfusion and ventilation), liver, spleen, kidney (structure and filtration rate), gall bladder, bone marrow, salivary and lacrimal glands, heart blood. Produced from Mo-99 in a generator. The most common radiopharmaceutical.
Thorium-227	18.7 d	Used for TAT, decays to Ra-223.
Xenon-133	5 d	Used for pulmonary (lung) ventilation studies.
Yttrium-90	64 h	arthritis in larger synovial joints. Pure beta emitter and of growing significance in therapy, especially liver cancer. Radioisotopes of gold and ruthenium are also used in brachytherapy. * fission product

Cyclotron produced radionuclides



Radioisotope	Half-life	Medical use / notes
Actinium-225	10 d	Used for targeted alpha therapy (TAT), especially prostate cancers.
Astatine-211	7.2 h	Used for targeted alpha therapy (TAT).
Bismuth-213	46 min	Used for targeted alpha therapy (TAT).
Carbon-11	20.4 min	Positron emitter used in PET to study brain physiology and pathology, including epilepsy, dementia, psychiatry, and neuropharmacology; also used in cardiology.
Nitrogen-13	10 min	Positron emitter used in PET to study brain physiology and pathology, including epilepsy, dementia, psychiatry, and neuropharmacology; also used in cardiology.
Oxygen-15	2 min	Positron emitter used in PET to study brain physiology and pathology, including epilepsy, dementia, psychiatry, and neuropharmacology; also used in cardiology.
Fluorine-18	110 min (listed for FLT, FMISO and 18F-choline)	PET tracer for imaging malignant tumours. Fluorine-18 in FDG is important for cancer detection and monitoring treatment progress. The source also groups F-18 with C-11, N-13 and O-15 as PET positron emitters.
Cobalt-57	272 d	Used as a marker to estimate organ size and in in-vitro diagnostic kits.
Copper-64	13 h	Used to study disorders of copper metabolism (including Wilson's and Menkes diseases), for PET tumour imaging, and in cancer therapy.
Copper-67	2.6 d	Beta emitter used in therapy.
Gallium-67	78 h	Used for tumour imaging and locating inflammatory lesions, including infections.
Gallium-68	68 min	Positron emitter used in PET and PET-CT; can be obtained from a germanium-68 generator.
Germanium-68	271 d	Parent isotope in a generator used to produce gallium-68.
Indium-111	2.8 d	Used for specialist diagnostic studies, including brain, infection and colon-transit studies; also used to locate blood clots, inflammation and rare cancers.
Iodine-123	13 h	Used for diagnosis of thyroid function; gamma emitter without the beta radiation of iodine-131.
Iodine-124	4.2 d	PET tracer with a longer half-life than fluorine-18; also used to image the thyroid with PET.
Krypton-81m	13 s	Gas used to produce functional images of pulmonary ventilation, and to assess lung disease and function. Produced from rubidium-81 (half-life 4.6 h).
Rubidium-82	1.26 min	PET agent used in myocardial perfusion imaging.
Strontium-82	25 d	Parent isotope in a generator used to produce rubidium-82.
Thallium-201	73 h	Used to diagnose coronary artery disease and other heart conditions, including heart-muscle damage; also used to locate low-grade lymphomas and in cardiac stress testing.

Personalized medicine

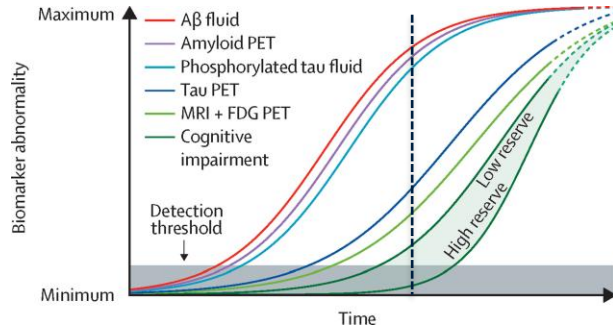


- Correct disease diagnosis
- Identification of treatment
- Monitoring of treatment efficacy

Radiopharmaceutical design, quantitative imaging, image interpretation, AI

- Appropriately designed radiopharmaceutical's uptake and distribution can be indicative of health state/specific disease mechanism
- Disease can result in subtle changes in multiple processes: need optimal radiopharmaceutical, sensitive imaging equipment, and advanced analysis
- Accurate dosimetry is required for treatment administration

Towards personalized medicine – brain illness (example dementia)

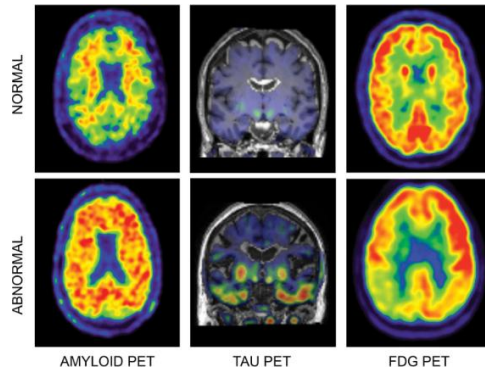


Jack et al., Lancet
Neurology 2022

A Deep Learning Model to Predict a Diagnosis of Alzheimer Disease by Using ^{18}F -FDG PET of the Brain

Yiming Ding • Jae Ho Sohn, MD, MS • Michael G. Kawczynski, MS • Hari Trivedi, MD • Roy Harnish, MS • Nathaniel W. Jenkins, MS • Dmytro Lituev, PhD • Timothy P. Copeland, MPP • Marian S. Aboian, MD, PhD • Carina Mari Aparici, MD • Spencer C. Behr, MD • Robert R. Flavell, MD, PhD • Shih-Ying Huang, PhD • Kelly A. Zalocusky, PhD • Lorenzo Nardo, PhD • Youngbo Seo, PhD • Randall A. Hawkins, MD, PhD • Miguel Hernandez Pampaloni, MD, PhD • Dexter Hadley, MD, PhD • Benjamin L. Franc, MD, MS

Radiology 2019; 290:456–464



Conclusion: By using fluorine 18 fluorodeoxyglucose PET of the brain, a deep learning algorithm developed for early prediction of Alzheimer disease achieved 82% specificity at 100% sensitivity, an average of 75.8 months prior to the final diagnosis.

© RSNA, 2018

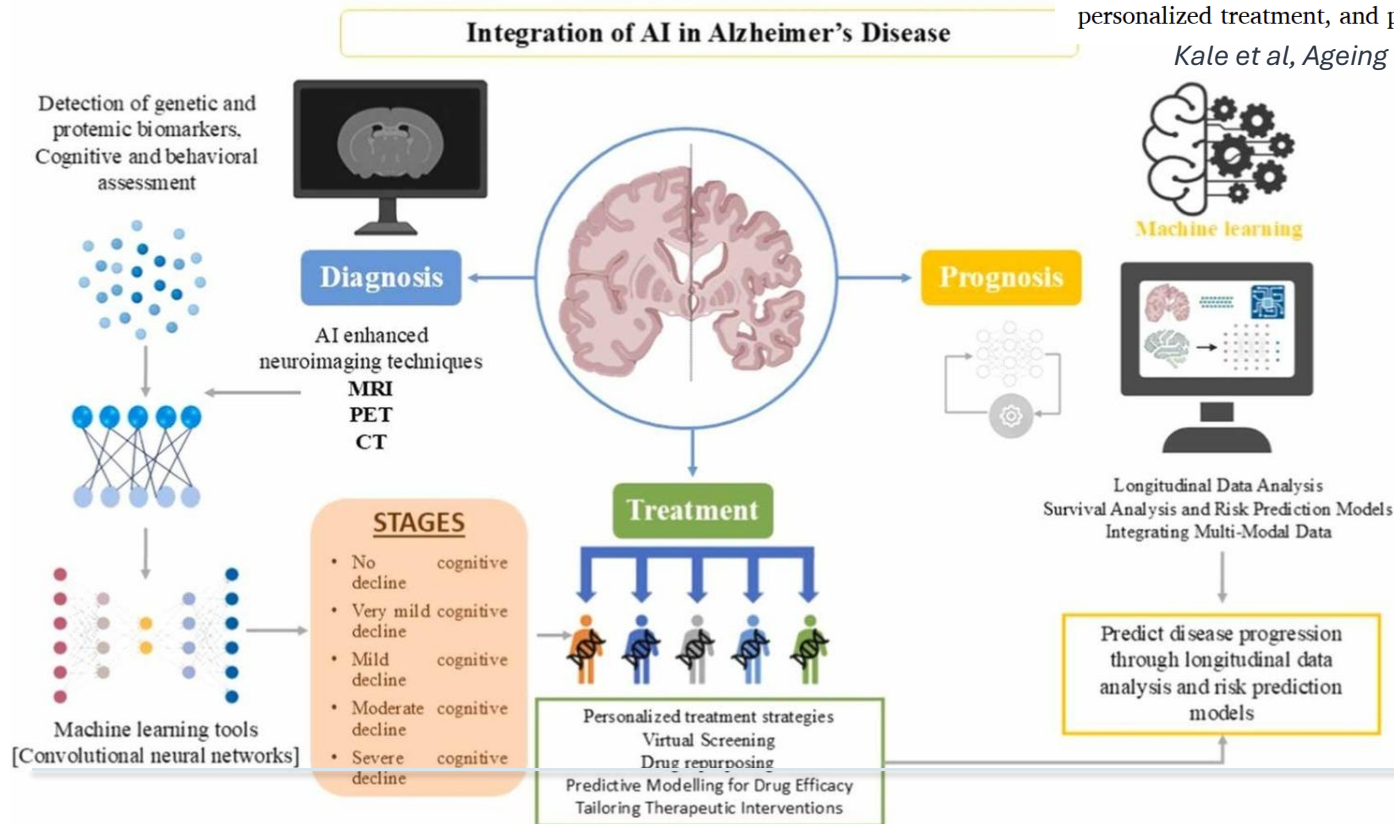
en Kate et al. Alzheimer's
Research & Therapy (2018)

Towards personalized medicine – brain illness (example dementia – one step further (multimodality))



AI-driven innovations in Alzheimer's disease: Integrating early diagnosis, personalized treatment, and prognostic modelling

Kale et al, Ageing research Reviews 2024



Treatment administration and monitoring - theranostic



Recent advances in theranostics and oncology. PET: emerging radionuclides and targets

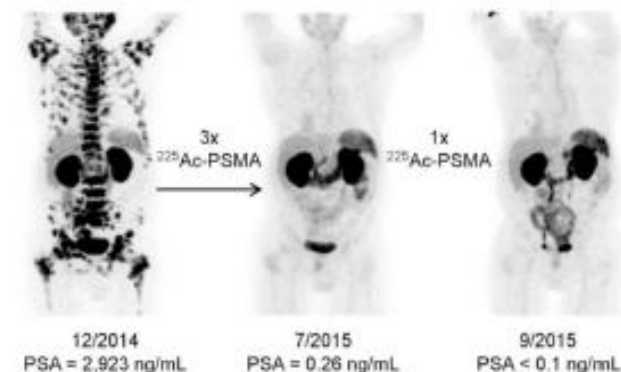
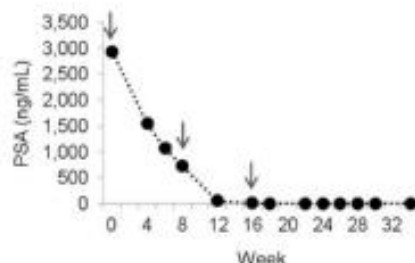
Tadashi Watabe^{1,2}, Kenji Hirata³, Mami Iima⁴, Masahiro Yanagawa¹, Tsukasa Saido⁵, Akihiko Sakata⁶, Satoru Ide⁷, Maya Honda⁸, Ryo Kurokawa⁹, Kentaro Nishioka¹⁰, Mariko Kawamura¹¹, Rintaro Ito¹¹, Koji Takumi¹², Seitaro Oda¹³, Shunsuke Sugawara¹⁴, Keitaro Sofue¹⁵, Daiju Ueda¹⁶, Shinji Naganawa¹¹

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	¹⁷⁷ Lu	²²⁵ Ac	²¹³ Pb	²¹¹ At
Radiation	β	α	α(β)	α
Half-life	7 days	10 days	10.6 h	7.2 h
Therapeutic effect	+	++	++	++
Exposure to surroundings	High	Low	Low-moderate	Low
Isolation	Required	Not required	Not required?	Not required
Outpatient treatment	x*	○	○?	○
Domestic production	x	x	x	○
Cyclotron manufacturing	x	Possible	x	○
Imaging	○	x	○	○
Approval status	FDA approved	No	No	No

+: moderate therapeutic effect; ++: strong therapeutic effect; ?: data or consensus currently limited or under investigation; ○: generally feasible; x: not generally feasible; *: depending on regulatory authority regulations in each country)

Example of emerging radionuclides for theranostics and TAT



Imaging with ⁶⁸Ga-PSMA-11

- **Patient selection criteria** are important
- TAT ideal for treating **micrometastases, small cell clusters, and minimal residual disease**: short tissue penetration depth (~2 to 10 cell diameters)
- **AI** can optimize patient selection: multimodal integration, imaging and tomour segmentation, dosimetry optimization, toxicity and risk stratification through predictive models

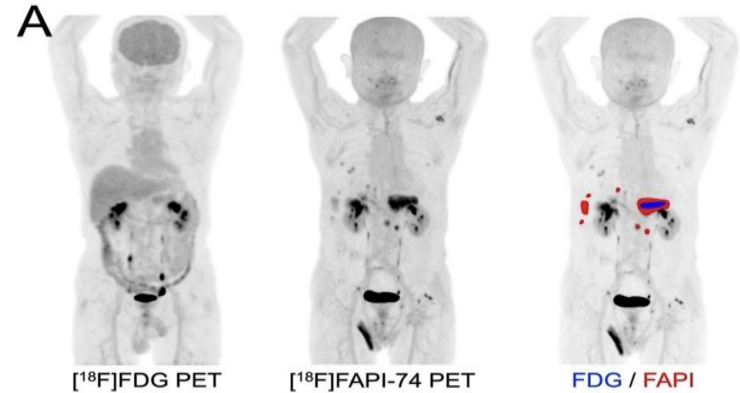
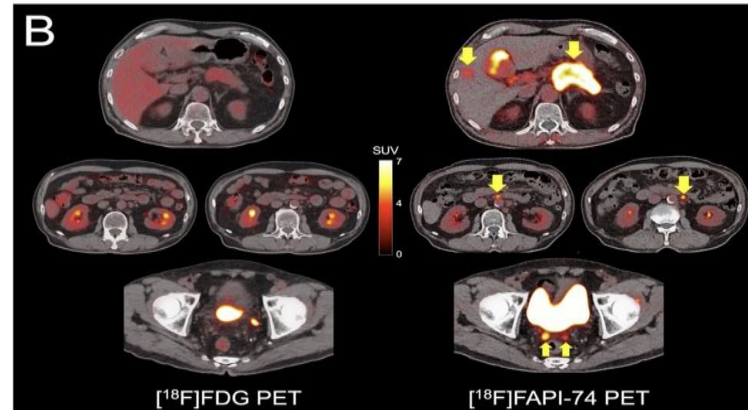
Towards personalized medicine - different imaging targets



New imaging targets/tracers

Tumours are heterogenous

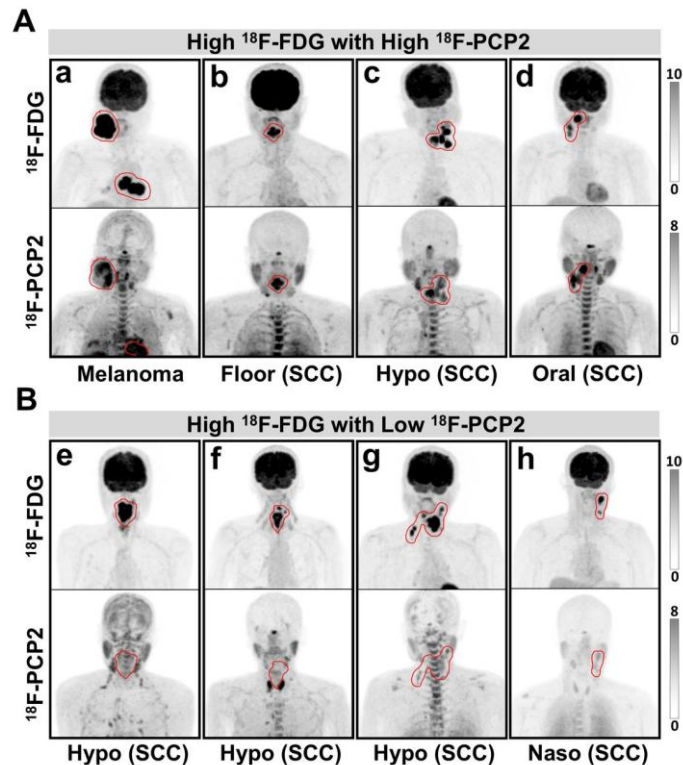
Example: Fibroblast activation protein inhibitor (**FAPi**) targets cancer associated fibroblasts – can be an independent prognostic factor in some cancers



Towards personalized medicine – immunotherapy



New targets/tracers: immuno-therapy related imaging (e.g. [^{18}F]AIF-NOTA-PCP2 PD-L1-targeted peptide-based tracer – shown to correlate with PD-L1 expression determined by immunohistochemistry)



Multi-tracer – imaging

FDG PET is effective for assessing tumor metabolic activity but shows limited ability to predict PD-L1 expression, with only 24.09% of PD-L1 variation explained by FDG uptake.

This highlights the biological divergence between glycolytic activity and immune regulation, as PD-L1 expression is more influenced by the immune microenvironment.

Combining FDG PET with immuno-PET tracers like [^{18}F]AIF-NOTA-PCP2 could offer a more comprehensive understanding of tumor biology, enhancing patient stratification and guiding personalized immunotherapy.

Wang Y, Liu Z, Hu M, Yu J. Can [^{18}F]FDG-PET/CT predict PD-L1 expression in head and neck carcinoma? a head-to-head comparison with a novel pd-l1 PET tracer. *J Nucl Med.* 2025;66(supplement 1): 251095, **Image of the year at the SNMMI**

AI can help in target identification and affinity prediction

Towards Personalized Medicine – integrated approach



Toward Integrated Clinical-Computational Nuclear Medicine

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PET Clin 21 (2026) 17-31
<https://doi.org/10.1016/j.cpet.2025.09.003>

AI plays a role in every step!



Raising commercial interest in nuclear medicine



Nuclear Medicine in 2024: A Year of Breakthroughs and Challenges

Radiopharmaceutical boom

Companies were eager to tap into the power of radiopharmaceuticals to offer more precise and effective treatments for cancer and other diseases, leading to a flurry of activity focused on developing innovative therapies

Key trends driving the market

- Focus on alpha emitters
- Expansion of production facilities
- Advancement in theranostics

NEEDS and CHALLENGES

Nuclear Medicine requires a complex ecosystem



Basic Science	
Responsibilities	Specialists
Targetry; accelerator and reactor development	Cyclotron and reactor engineers
Production and isolation of radionuclides	Nuclear chemists
Development of radiosynthetic methods and cGMP processes	Radiochemists and radiopharmacists
Quality control testing and method validation	Radioanalytical chemists
<i>In vitro</i> and <i>in vivo</i> evaluation	Pharmacologists, radiopharmaceutical chemists, radiation biologists, and cancer biologists
Clinical Translation	
Responsibilities	Specialists
Preclinical proof-of-concept studies	Pharmacologists, radiopharmaceutical chemists, radiation biologists, and cancer biologists
Preclinical dosimetry	Medical physicists
Preclinical pharmacology and toxicology studies	Pharmacologists and toxicologists
Generation of clinical protocols and preparation of regulatory filings.	Nuclear medicine physicians, health physicists, medical physicists, radiochemists, radiopharmacists, and regulatory scientists.
cGMP manufacturing	Radiochemists, QC chemists, and radiopharmacists
Clinical trials	Nuclear medicine physicians, biostatisticians, clinical trial coordinators, and study coordinators
Routine Clinical Use	
Responsibilities	Specialists
Patient referral for imaging and treatment with radiopharmaceuticals	Affiliated physicians (<i>e.g.</i> , urologists, medical oncologists, radiation oncologists, and interventional radiologists, often via multidisciplinary tumour boards)
Administration of radiopharmaceutical tracers and supervision of clinical protocols	Nuclear medicine physicians, radiation oncologists, nurses, and technologists
Interpretation of imaging data	Nuclear medicine physicians and radiologists
Human dosimetry	Medical physicists
Helping patients (and their loved ones) navigate the healthcare system	Patient advocates

Lancet Oncol. Author manuscript; available in PMC: 2025 Jun 1.

Published in final edited form as: Lancet Oncol. 2024 Jun;25(6):e250–e259. doi: [10.1016/S1470-2045\(24\)00037-8](https://doi.org/10.1016/S1470-2045(24)00037-8)

Trends in Nuclear Medicine and the Radiopharmaceutical Sciences in Oncology: Workforce Challenges and Training in the Age of Theranostics

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Key challenges



1. Supply Chain Issues

- Limited production facilities
- Growing demand
- Geopolitical factors



2. Safety concerns

- Complex dosimetry
- Long term effects
- Combination therapy

Is there a role for SMRs in radionuclide production?

3. Regulatory hurdles

4. Manufacturing scalability

- Cost
- Skilled workforce shortage
- Radiopharmaceutical transportation logistics



5. Reimbursement and access

6. Technological advancements

REVIEW

Open Access



Novel radionuclides: demand, production and distribution for translational research in Europe

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Goal

To explore the requirements of end users in nuclear medicine from industrial, scientific, and clinical backgrounds.

PRISMAP - Production of high purity Isotopes by mass Separation for Medical Application program Survey 2022+

Responses received

- 48 research institutions represented by 25 universities
- 15 public laboratories and 8 others
- 40 respondents are preclinical/clinical researchers
- 16 are working in the field of radionuclide production.

Results



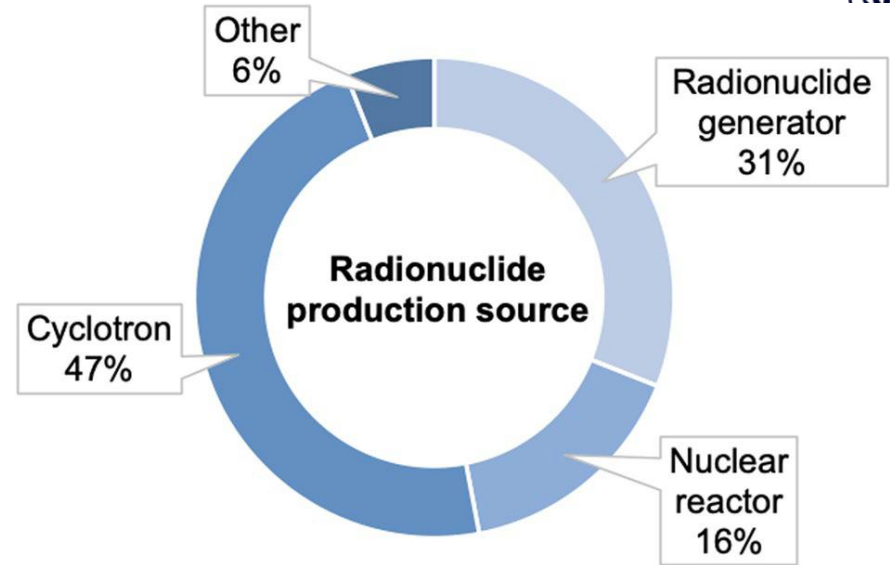
SPECT radionuclides in clinical use

^{99m}Tc , ^{111}In , ^{123}I , ^{90}Y , ^{131}I , ^{177}Lu , ^{223}Ra

PET radionuclides are

^{11}C , ^{13}N , ^{15}O , ^{18}F

- **Increasing demand for ^{225}Ac**
- **Considering increased use of ^{44}Sc , ^{47}Sc , ^{64}Cu , ^{67}Cu , ^{89}Zr , ^{149}Tb , ^{152}Tb , ^{155}Tb , ^{161}Tb , $^{165}\text{Er}/^{169}\text{Er}$, ^{177}Lu , ^{188}Re , ^{211}At , ^{225}Ac .**



Production is not uniformly distributed across Europe

**Table 2** Major research reactors in Europe according to the IAEA database

Nr	Reactor	Country	Operator	Produced therapeutic radionuclides
1	MARIA	Poland	POLATOM	^{32}P , ^{89}Sr , ^{90}Y , ^{131}I , ^{153}Sm , ^{166}Ho , ^{177}Lu , ^{186}Re , ^{188}Re
2	HFR	Netherlands	NRG	^{89}Sr , ^{90}Y , ^{166}Ho , ^{169}Er , ^{177}Lu , ^{212}Pb
3	BR2	Belgium	SCK-CEN	^{89}Sr , ^{90}Y , ^{131}I , ^{153}Sm , ^{177}Lu , ^{186}Re , ^{188}Re , $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$
4	FRMII	Germany	Technical University of Munich	^{166}Ho , ^{177}Lu
5	RHF	France	Institut Laue-Langevin	^{47}Sc , ^{111}Ag , ^{161}Tb , ^{169}Er , ^{175}Yb , ^{177}Lu , ^{188}Re
6	LVR-15	Czech Republic	CVR Řež	^{131}I , ^{153}Sm , ^{166}Ho , ^{177}Lu , ^{186}Re , ^{188}Re
7	BRR	Hungary	BNC/AEKI	^{32}P , ^{90}Y , ^{131}I , ^{153}Sm , ^{166}Ho , ^{177}Lu

Table 3 List of radionuclide generators produced used or studied by respondent institutions

Nr.	Respondent	Generators
1	Eckert & Ziegler Radiopharma (Germany)	$^{68}\text{Ge}/^{68}\text{Ga}$
2	GIP Arronax (France)	$^{82}\text{Sr}/^{82}\text{Rb}$, $^{68}\text{Ge}/^{68}\text{Ga}$
3	Oslo University Hospital (Norway)	$^{224}\text{Ra}/^{212}\text{Pb}$
4	SCK CEN (Belgium)	$^{225}\text{Ac}/^{213}\text{Bi}$, $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$
5	CNRS CEMHTI (France)	$^{165}\text{Tm}/^{165}\text{Er}$
6	Orano (France)	$^{224}\text{Ra}/^{212}\text{Pb}$
7	Delft University of Technology (Netherlands)	$^{99}\text{Mo}/^{99\text{m}}\text{Tc}$, $^{188}\text{W}/^{188}\text{Re}$, $^{47}\text{Ca}/^{47}\text{Sc}$, $^{166}\text{Dy}/^{166}\text{Ho}$

- Transportation is a problem, so is accessibility of theranostic capabilities
- Fragmented and unharmonized procedure for import/export and clinical translation

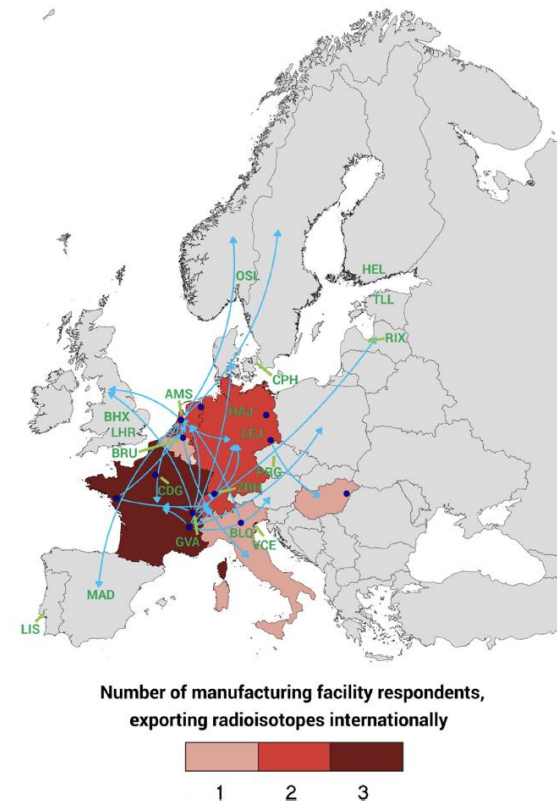


Fig. 3 Radionuclide distribution from European manufacturers to recipients (by countries)

Other limitations



- Limitations in infrastructure
- Shortage of staff
- Shortage of expertise
- Production capacity and target material supply
- Other financial or managerial issues

Possibilities to teach and train students, staff and to transfer knowledge, as indicated by responders: a limitations, which can be addressed through more **open communication** between institutions.

Factors limiting democratization of nuclear medicine in LMIC



- Infrastructure cost (example: 1 SPECT scanner may serve 33M people (compared to 57K in HIC)
- Availability of radiopharmaceuticals – global supply chains
- Staffing
- Training
- Lack of clear regulatory guidelines

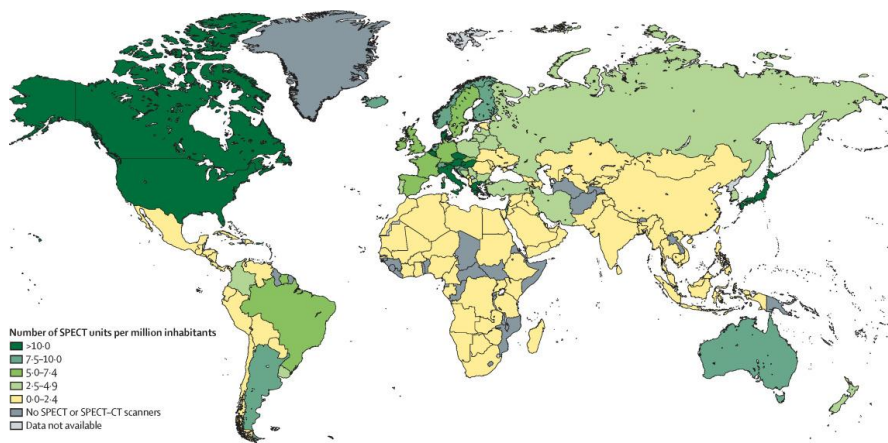
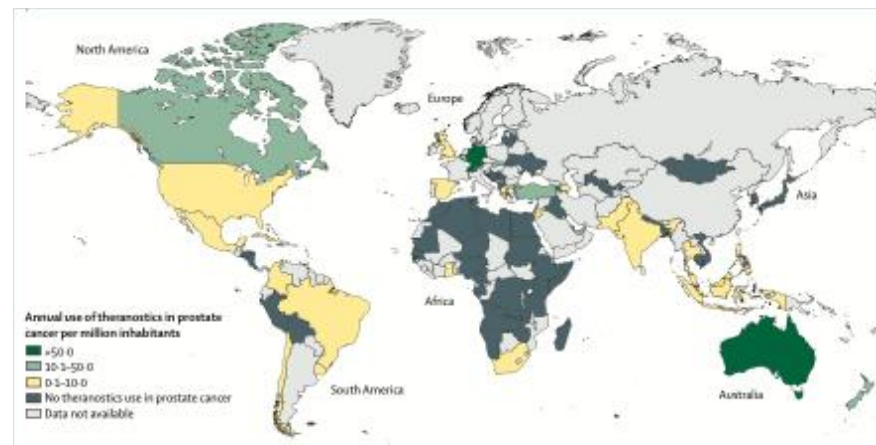


Figure 10: Use of ^{177}Lu PSMA and ^{225}Ac PSMA in prostate cancer
The global distribution of the annual use of radionuclides and theranostics to treat prostate cancer per million inhabitants, in 82 countries surveyed by the IAEA for this Lancet Oncology Commission and a further 84 countries from IAEA database sources (appendix p 10). IAEA=International Atomic Energy Agency. PSMA=prostate-specific membrane antigen.

Hricak et al Lancet Oncology 2021, Medical imaging and nuclear Medicine

Global Challenges in the Provision of Theranostic Services The International Atomic Energy Agency (IAEA) Perspective

World J Nuclear Med 2025;24:238-243.

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SMRs produced radionuclides could have an impact



Most suitable candidates for SMR production:

- ^{99}Mo : parent isotope of $^{99\text{m}}\text{Tc}$
- ^{177}Lu
- ^{60}Co
- ^{131}I
- ^{125}I
- ^{90}Y

There is need, but still in research stage

Conclusion



Nuclear medicine is increasingly more important in health management

Quantitative molecular imaging can support diagnosis, treatment selection and response monitoring.

With recent advances nuclear medicine can contribute significantly to personalized care

For example, theranostics and targeted imaging can deliver subject specific care

Access depends on the ecosystem

Reliable isotope production, transport, infrastructure and trained staff are essential.

SMRs: potential, not yet a near-term solution

Some medical isotopes are candidates for SMR production, but the approach remains at a research stage.

Nuclear medicine can expand personalized care when production, evidence and access advance together.