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# Physical characteristics of novel nanomagnetic radiopharmaceuticals: a review

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**nanomagnetic radiopharmaceuticals; drugs; cancer; nuclear medicine; nanoparticles**

## ABSTRACT

Hybrid nanomagnetic radiopharmaceuticals represent a frontier in targeted therapy and diagnostic imaging. These compounds synergistically combine magnetic nanoparticles with radiopharmaceutical agents in order to enhance the precision, delivery, and therapeutic efficacy of nuclear medicine interventions. This review summarizes their physicochemical properties, presents their mechanisms of action, and discusses their translational potential across a range of clinical applications.

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## 1. Introduction

Hybrid nanomagnetic radiopharmaceuticals integrate nanotechnology with radiolabelled compounds in order to enable targeted therapies, particularly for oncological applications. These agents employ externally guided magnetic nanoparticles (MNPs) for site-specific drug delivery, and incorporate radioisotopes for both therapeutic irradiation and diagnostic imaging. Their nanoscale dimensions enhance biological interactions and biodistribution, thereby establishing a theranostic paradigm essential for personalized medicine and early disease detection[1].

By expanding the diagnostic and therapeutic capabilities of nuclear medicine, hybrid nanomagnetic radiopharmaceuticals offer precise targeting of malignant tissues while minimizing collateral damage to healthy cells. The integration of MNPs with radiopharmaceuticals facilitates simultaneous diagnosis and treatment, thereby advancing individualized therapeutic strategies. Moreover, their compatibility with imaging modalities such as positron emission tomography (PET) and single photon emission computed tomography (SPECT) strengthens tumor visualization and monitoring, which is pivotal for future innovations in nuclear medicine[2,3].

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## 2. Nanoparticles in radiopharmaceuticals

Nanoparticles (NPs) are central to the development of hybrid nanomagnetic radiopharmaceuticals, serving both therapeutic and diagnostic functions. Their unique physicochemical properties (particularly size and magnetism) enhance targeted drug delivery, imaging resolution, and therapeutic efficacy, thereby supporting precision medicine. Radiopharmaceuticals, which contain radionuclides, function by emitting detectable gamma rays or particulate radiation for diagnostic or therapeutic purposes. Common diagnostic radionuclides include technetium-99m and gallium-68, typically used in conjunction with PET and SPECT imaging. Therapeutic radionuclides such as iodine-131 deliver localized radiation for cancer treatment. The selection of radionuclides must consider energy emission profiles and half-lives so as to optimize safety and clinical effectiveness[1,4].

## 3. Mechanisms of targeted delivery

Targeted delivery mechanisms in hybrid nanomagnetic radiopharmaceuticals include both passive and active strategies. Passive targeting exploits the enhanced permeability and retention effect, whereby NPs preferentially accumulate in tumor tissues due to aberrant vascular architecture[4]. Active targeting involves functionalizing NPs with ligands or biomolecules that selectively bind to overexpressed receptors on diseased cells, thereby increasing binding specificity and promoting cellular internalization[5]. Advanced imaging techniques facilitate real-time assessment of these delivery mechanisms, thereby enabling visualization of radiopharmaceutical distribution and accumulation. The combined use of passive and active targeting may enhance therapeutic efficacy while minimizing systemic toxicity by concentrating therapeutic agents at pathological sites[3].

## 4. Potential applications in therapy and imaging

Hybrid nanomagnetic radiopharmaceuticals offer transformative potential in oncology by merging targeted therapy with advanced imaging capabilities. The advent of theranostic agents (i.e., NPs engineered for both imaging and treatment) permits real-time monitoring of drug biodistribution and therapeutic response *via* modalities such as magnetic resonance imaging (MRI) and PET[6]. This dual functionality supports the development of personalized treatment regimens tailored to the molecular and anatomical characteristics of individual tumours, thereby improving clinical outcomes[7].

## 5. Enhanced efficacy and precision

These hybrid agents are redefining diagnostic imaging by improving the sensitivity and specificity of cancer detection. PET utilizes radiolabelled ligands in order to identify tumor-specific biomarkers, enabling precise localization and informed therapeutic decisions[8]. Concurrently, MRI benefits from hybrid NPs serving as contrast enhancers, which improve image resolution and delineation of tumor margins and adjacent tissues[7–10]. The incorporation of multifunctional NPs into imaging platforms allows for the integration of diverse modalities, thereby enhancing diagnostic accuracy and clinical utility.

## 6. Reduced side-effects and toxicity profiles

Hybrid nanomagnetic radiopharmaceuticals contribute to safer cancer therapies by localizing drug activity at tumor sites and minimizing exposure to non-target tissues. This targeted approach reduces systemic toxicity and permits lower therapeutic dosages[10]. MNPs also stabilize therapeutic agents against degradation and sustain drug release over extended periods. Surface modifications of NPs improve biocompatibility, attenuate immunogenic responses, and enhance cellular uptake, collectively reducing adverse effects and improving patient tolerability in radiopharmaceutical regimens.

## 7. Challenges and limitations

Despite their promise, hybrid nanomagnetic radiopharmaceuticals face significant regulatory and manufacturing challenges. Regulatory agen-

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**Table 1.** Examples of novel hybrid nanomagnetic radiopharmaceutical drugs, including their key components, properties, applications, and clinical significance.

| Hybrid nanomagnetic radiopharmaceutical | Nanoparticle type | Radioisotope | Targeting ligand | Application | Clinical significance |
|---|---|---|---|---|---|
| Iron oxide nanoparticles + iodine-131 | Iron oxide ($Fe_3O_4$) | Iodine-131 | Antibodies / peptides | Treatment of thyroid cancers | Selective targeting of thyroid tissues for therapy |
| Gold nanoparticles + technetium-99m | Gold nanoparticles | Technetium-99m | Folate-targeted ligands | Imaging of tumors | Improved imaging contrast for cancer detection |
| Silica nanoparticles + lutetium-177 | Silica nanoparticles | Lutetium-177 | Peptide ligands | Targeted radiation therapy | Effective treatment for neuroendocrine tumors |
| Magnetic hybrid nanoparticles + gallium-68 | Magnetic iron oxide | Gallium-68 | Monoclonal antibodies | PET imaging of cancer | Enhanced specificity for tumor localization |
| Polymeric nanoparticles + samarium-153 | Polymeric nanospheres | Samarium-153 | Tumor-specific peptides | Palliative treatment for bone pain | Pain relief from bone metastases |
| Liposomal nanoparticles + radium-223 | Lipid-based nanocarriers | Radium-223 | None or amino acid ligands | Treatment of metastatic prostate cancer | Targeted radiation therapy with minimal side effects |

cies such as the US Food and Drug Administration (FDA) and the European Medicines Agency (EMA) impose stringent requirements for complex nanotheranostic systems. Ambiguities in regulatory frameworks – particularly concerning the intersection of chemical and nanotechnological domains – necessitate comprehensive characterization data, which can delay clinical translation[9]. The rapid evolution of nanotechnology may outpace existing regulatory mechanisms, complicating the assessment and approval of novel agents. Nonetheless, regulatory oversight remains essential for ensuring patient safety. Personalized radiopharmaceuticals, enabled by MRI and PET monitoring, offer tailored therapeutic options, but their reproducible manufacture is technically demanding. Each production step must be tightly controlled to prevent variability that could compromise efficacy or safety. Scalable production methods, including emerging technologies such as three-dimensional (3D) printing, require further refinement in order to ensure batch consistency.

## 8. Future perspectives and innovations in the field

Advances in nanomedicine are reshaping disease diagnosis, monitoring, and treatment. Multifunctional NPs (termed “nanotheranostics”) enable simultaneous imaging and therapy, enhancing medical precision through integration with established modalities such as PET and MRI. Immunofluorescent sensors, functioning as biosensors, facilitate early disease detection. The convergence of artificial intelligence and machine learning with precision medicine accelerates diagnostic workflows and supports the development of individualized treatment strategies[7–9].

## 9. Conclusion

Hybrid nanomagnetic radiopharmaceuticals are catalysing significant progress in medical imaging and cancer therapy. Their unique magnetic and radiolabelling properties enhance diagnostic accuracy and therapeutic precision. The fusion of nanotechnology with radiopharmaceutical science underpins the evolution of personalized medicine, offering novel avenues for patient-centered care.

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**Conflicts of interest**

None exist.

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