Advances and Challenges in the Application of Radiolabeled Magnetic Nanoparticles for Cancer Theranostics

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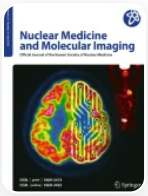

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Abstract

Radiolabeled magnetic nanoparticles (MNPs), particularly superparamagnetic iron oxide nanoparticles (SPIONs), have gained significant attention in the field of cancer theranostics due to their potential in targeted therapy and molecular imaging. This review highlights recent advancements in the development of various radiolabeled SPIONs, including those functionalized with polyethylene glycol (PEG), DTPA, and other targeting agents. These nanoparticles are designed for multiple clinical applications, including hyperthermia, magnetic resonance imaging (MRI), and radiotherapy. However, the translation of these promising nanostructures into clinical practice faces several challenges, such as issues with surface functionalization, toxicity, stability, and the

complexities of multimodal imaging. The review also explores creative approaches to overcome these challenges, such as designing multicomponent nanostructures, utilizing chelator-based and chelator-free radiolabeling techniques, employing click chemistry for radiolabeling, and enhancing biocompatibility methods. Ultimately, radiolabeled SPIONs have the potential to revolutionize cancer treatment and imaging, but further optimization is required to overcome existing obstacles and enhance their clinical applicability.

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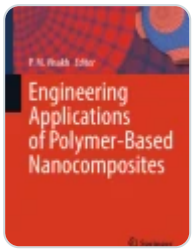

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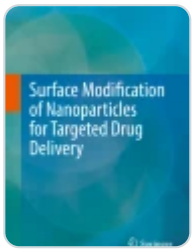

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Data Availability

Data sharing not applicable to this article as no datasets were generated in the current study.

References

1. Farzanegan Z, Tahmasbi M. Magnetic nanoparticles based hyperthermia for cancer treatment: A systematic review. 2022.

2. Bray F, Ferlay J, Soerjomataram I, Siegel RL, Torre LA, Jemal A. Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J Clin. 2018;68(6):394–424.

PubMed Google Scholar

3. Ferlay J, Ervik M, Lam F, Colombet M, Mery L, Piñeros M. Global cancer observatory: cancer today. Lyon, France: international agency for research on cancer; 2018.

Google Scholar

4. Sung H, Ferlay J, Siegel RL, Laversanne M, Soerjomataram I, Jemal A, Bray F. Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J Clin. 2021;71(3):209–49.

PubMed Google Scholar

5. Bray F, Laversanne M, Sung H, Ferlay J, Siegel RL, Soerjomataram I, Jemal A. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. Cancer J Clin. 2024;74(3):229–63.

Article Google Scholar

6. Torre L, Siegel R, Jemal A. Global cancer facts & figures. Atlanta: American Cancer Society. 2015;2.

7. Talluri S, Malla RR. Superparamagnetic iron oxide nanoparticles (SPIONs) for diagnosis and treatment of breast, ovarian and cervical cancers. Curr Drug Metab. 2019;20(12):942–5.

Article CAS PubMed Google Scholar

8. Lamichhane N, Sharifabad ME, Hodgson B, Mercer T, Sen T. Superparamagnetic iron oxide nanoparticles (SPIONs) as therapeutic and diagnostic agents. Nanoparticle therapeutics: Elsevier; 2022. pp. 455–97.

Google Scholar

9. Hadei SK, Alvandi M, Ramezani M, Aloosh O, Shaghaghi Z, Moradi A. Applying wells score to inconclusive perfusion only modified PIOPED II (prospective investigation of pulmonary embolism diagnosis II) readings in order to optimize the lung scintigraphy diagnostic yield in acute pulmonary embolism detection. Ann Nucl Med. 2020;34:521–6.

Article PubMed Google Scholar

10. Awad NS, Salkho NM, Abuwatfa WH, Paul V, AlSawaftah NM, Husseini GA. Tumor vasculature vs tumor cell targeting: understanding the latest trends in using functional nanoparticles for cancer treatment. OpenNano. 2023;11:100136.

Article CAS Google Scholar

11. McKay A, Pantoja C, Hall R, Matthews S, Spalding P, Banerjee R. Patient understanding and experience of non-invasive imaging diagnostic techniques and the liver patient pathway. J Patient-Reported Outcomes. 2021;5:1–14.

Article Google Scholar

12. Yu Y, Jain B, Anand G, Heidarian M, Lowe A, Kalra A. Technologies for non-invasive physiological sensing: status, challenges, and future horizons. Biosens Bioelectronics: X. 2024;16:100420.

CAS Google Scholar

13. Feng Z, Fan H, Cheng L, Zhang H, Fan H, Liu J. Advanced biomimetic nanomaterials for non-invasive disease diagnosis. Front Mater. 2021;8: 664795.

Article Google Scholar

14. Hussain S, Mubeen I, Ullah N, Shah S, Khan BA, Zahoor M, et al. Modern diagnostic imaging technique applications and risk factors in the medical field: A review. Biomed Res Int. 2022;2022:5164970.

Article PubMed PubMed Central Google Scholar

15. Vangijzegem T, Lecomte V, Ternad I, Van Leuven L, Muller RN, Stanicki D, Laurent S. Superparamagnetic iron oxide nanoparticles (SPION): from fundamentals to state-of-the-art innovative applications for cancer therapy. Pharmaceutics. 2023;15(1):236.

Article CAS PubMed PubMed Central Google Scholar

16. Singh V, Theranostics. Integrated diagnostics and therapy using nanomedicine. Nanomedicine: Springer; 2024. pp. 505–30.

Google Scholar

17. Jeyamogan S, Khan NA, Siddiqui R. Application and importance of theranostics in the diagnosis and treatment of cancer. Arch Med Res. 2021;52(2):131–42.

Article CAS PubMed Google Scholar

18. Kang SJ, Jeong HY, Kim MW, Jeong IH, Choi MJ, You YM, et al. Anti-EGFR lipid micellar nanoparticles co-encapsulating quantum dots and paclitaxel for tumor-targeted theranosis. Nanoscale. 2018;10(41):19338–50.

Article CAS PubMed Google Scholar

19. Alromi D, Seifalian A. Emerging application of magnetic nanoparticles for diagnosis and treatment of cancer. Polymers. 2021;13.

20. Hazarika D, Sarma S, Shankarishan P. Nanotechnology in cancer therapeutics, diagnosis, and management. BioTechnologia. 2024;105(3):287–303.

Article CAS PubMed PubMed Central Google Scholar

21. Nwabunwanne C, Aisida SO, Javed R, Akpomie kG, Awada C, Alshoaibi A, Ezema F. Magnetic nanoparticles: biosynthesis, characterization, surface functionalization and biomedical applications. J Indian Chem Soc. 2025;102(3):101617.

Article CAS Google Scholar

22. Colombo M, Carregal-Romero S, Casula MF, Gutiérrez L, Morales MP, Böhm IB, et al. Biological applications of magnetic nanoparticles. Chem Soc Rev. 2012;41(11):4306–34.

Article CAS PubMed Google Scholar

23. Kafrouni L, Savadogo O. Recent progress on magnetic nanoparticles for magnetic hyperthermia. Prog Biomater. 2016;5(3):147–60.

Article CAS PubMed PubMed Central Google Scholar

24. Albarqi HA, Wong LH, Schumann C, Sabei FY, Korzun T, Li X, et al. Biocompatible nanoclusters with high heating efficiency for systemically delivered magnetic hyperthermia. ACS Nano. 2019;13(6):6383–95.

Article CAS PubMed PubMed Central Google Scholar

25. Włodarczyk A, Gorgoń S, Radoń A, Bajdak-Rusinek K. Magnetite nanoparticles in magnetic hyperthermia and cancer therapies: challenges and perspectives. Nanomaterials. 2022;12(11):1807.

Article PubMed PubMed Central Google Scholar

26. Falagan-Lotsch P, Grzincic EM, Murphy CJ. New advances in nanotechnology-based diagnosis and therapeutics for breast cancer: an assessment of active-targeting inorganic nanoplatforms. Bioconjug Chem. 2017;28(1):135–52.

Article CAS PubMed Google Scholar

27. Shabestari Khiabani S, Farshbaf M, Akbarzadeh A, Davaran S. Magnetic nanoparticles: preparation methods, applications in cancer diagnosis and cancer therapy. Artif Cells Nanomed Biotechnol. 2017;45(1):6–17.

Article CAS PubMed Google Scholar

28. Song J, Hu Q, Huang J, Chen T, Ma Z, Shi H. MR targeted imaging for the expression of tenascin-C in cervical cancer. Br J Radiol. 2018;91(1090): 20170681.

Article PubMed PubMed Central Google Scholar

29. Yin X, Russek SE, Zabow G, Sun F, Mohapatra J, Keenan KE, et al. Large T1 contrast enhancement using superparamagnetic nanoparticles in ultra-low field MRI. Sci Rep. 2018;8(1):11863.

Article PubMed PubMed Central Google Scholar

30. Crosby D, Bhatia S, Brindle KM, Coussens LM, Dive C, Emberton M, et al. Early detection of cancer. Science. 2022;375(6586):eaay9040.

Article CAS PubMed Google Scholar

31. Frantellizzi V, Conte M, Pontico M, Pani A, Pani R, De Vincentis G. New frontiers in molecular imaging with superparamagnetic iron oxide nanoparticles (SPIONs): efficacy, toxicity, and future applications. Nucl Med Mol Imaging. 2020;54:65–80.

Article CAS PubMed PubMed Central Google Scholar

32. Lassenberger A, Scheberl A, Stadlbauer A, Stiglbauer A, Helbich T, Reimhult E. Individually stabilized, superparamagnetic nanoparticles with controlled shell and size leading to exceptional stealth properties and high relaxivities. ACS Appl Mater Interfaces. 2017;9(4):3343–53.

Article CAS PubMed PubMed Central Google Scholar

33. Uthaman S, Lee SJ, Cherukula K, Cho C-S, Park I-K. Polysaccharide-coated magnetic nanoparticles for imaging and gene therapy. Biomed Res Int. 2015;2015(1):959175.

PubMed PubMed Central Google Scholar

34. Akhtar N, Mohammed HA, Yusuf M, Al-Subaiyel A, Sulaiman GM, Khan RA. SPIONs conjugate supported anticancer drug doxorubicin's delivery: current status, challenges, and prospects. Nanomaterials. 2022;12(20):3686.

Article CAS PubMed PubMed Central Google Scholar

35. Suciu M, Ionescu C, Ciorîță A, Tripon S, Nica D, Al-Salami H, Barbu-Tudoran L. Applications of superparamagnetic iron oxide nanoparticles in drug and therapeutic delivery, and biotechnological advancements. Beilstein J Nanotechnol. 2020;11:1092–109.

Article CAS PubMed PubMed Central Google Scholar

36. Lapusan R, Borlan R, Focsan M. Advancing MRI with magnetic nanoparticles: a comprehensive review of translational research and clinical trials. Nanoscale Adv. 2024;6(9):2234–59. https://doi.org/10.1039/D3NA01064C

37. Xing Y, Zhao J, Conti PS, Chen K. Radiolabeled nanoparticles for multimodality tumor imaging. Theranostics. 2014;4(3):290–306.

Article PubMed PubMed Central Google Scholar

38. Bentivoglio V, Varani M, Lauri C, Ranieri D, Signore A. Methods for radiolabelling nanoparticles: PET use (Part 2). Biomolecules. 2022;12(10):1517.

Article CAS PubMed PubMed Central Google Scholar

39. Pellico J, Gawne PJ, de Rosales RT. Radiolabelling of nanomaterials for medical imaging and therapy. Chem Soc Rev. 2021;50(5):3355–423.

Article CAS PubMed Google Scholar

40. de Souza Albernaz M, Toma SH, Clanton J, Araki K, Santos-Oliveira R. Decorated superparamagnetic iron oxide nanoparticles with monoclonal antibody and diethylene-triamine-pentaacetic acid labeled with thechnetium-99m and galium-68 for breast cancer imaging. Pharm Res. 2018;35:1–9.

Article Google Scholar

41. Enrique M-A, Mariana O-R, Mirshojaei SF, Ahmadi A. Multifunctional radiolabeled nanoparticles: strategies and novel classification of radiopharmaceuticals for cancer treatment. J Drug Target. 2015;23(3):191–201.

Article CAS PubMed Google Scholar

42. Farzin L, Sheibani S, Moassesi ME, Shamsipur M. An overview of nanoscale radionuclides and radiolabeled nanomaterials commonly used for nuclear molecular imaging and therapeutic functions. J Biomed Mater Res A. 2019;107(1):251–85.

Article CAS PubMed Google Scholar

43. Nosrati S, Shanehsazzadeh S, Yousefnia H, Gholami A, Grüttner C, Jalilian AR, et al. Biodistribution evaluation of 166 Ho–DTPA–SPION in normal rats. J Radioanal Nucl Chem. 2016;307:1559–66.

Article CAS Google Scholar

44. Salih S, Alkatheeri A, Alomaim W, Elliyanti A. Radiopharmaceutical treatments for cancer therapy, radionuclides characteristics, applications, and challenges. Molecules. 2022;27(16):5231.

Article CAS PubMed PubMed Central Google Scholar

45. Forte E, Fiorenza D, Torino E, Costagliola di Polidoro A, Cavaliere C, Netti PA, et al. Radiolabeled PET/MRI nanoparticles for tumor imaging. J Clin Med. 2019;9(1):89.

Article PubMed PubMed Central Google Scholar

46. Ricci M, Frantellizzi V, Bulzonetti N, De Vincentis G. Reversibility of castration resistance status after Radium-223 dichloride treatment: clinical evidence and review of the literature. Int J Radiat Biol. 2019;95(5):554–61.

Article CAS PubMed Google Scholar

47. Sciarra A, Gentilucci A, Silvestri I, Salciccia S, Cattarino S, Scarpa S, et al. Androgen receptor variant 7 (AR-V7) in sequencing therapeutic agents for castratrion resistant prostate cancer: A critical review. Medicine. 2019;98(19):e15608.

Article CAS PubMed PubMed Central Google Scholar

48. Karakatsanis A, Daskalakis K, Stålberg P, Olofsson H, Andersson Y, Eriksson S, et al. Superparamagnetic iron oxide nanoparticles as the sole method for sentinel node biopsy detection in patients with breast cancer. Br J Surg. 2017;104(12):1675–85.

Article CAS PubMed Google Scholar

49. Mehralivand S, van der Poel H, Winter A, Choyke PL, Pinto PA, Turkbey B. Sentinel lymph node imaging in urologic oncology. Transl Androl Urol. 2018;7(5):887–902.

Article PubMed PubMed Central Google Scholar

50. Staník M, Macík D, Čapák I, Marečková N, Lžíčařová E, Doležel J. Sentinel lymph node dissection in prostate cancer using superparamagnetic particles of iron oxide: early clinical experience. Int Urol Nephrol. 2018;50(8):1427–33.

Article PubMed Google Scholar

51. Winter A, Tobias K, Susanne PT, Philipp G, Svenja E, Holger G, et al. Magnetic resonance Sentinel lymph node imaging and magnetometer-guided intraoperative detection in prostate cancer using superparamagnetic iron oxide nanoparticles. Int J Nanomed. 2018;13(null):6689–98.

Article CAS Google Scholar

52. Mekseriwattana W, Srisuk S, Kriangsaksri R, Niamsiri N, Prapainop K. The impact of serum proteins and surface chemistry on magnetic nanoparticle colloidal stability and cellular uptake in breast cancer cells. AAPS PharmSciTech. 2019;20:1–9.

Article Google Scholar

53. Zhang L, Jin R, Sun R, Du L, Liu L, Zhang K, et al. Superparamagnetic iron oxide nanoparticles as magnetic resonance imaging contrast agents and induced autophagy response in endothelial progenitor cells. J Biomed Nanotechnol. 2019;15(2):396–404.

Article CAS PubMed Google Scholar

54. Patil RM, Thorat ND, Shete PB, Bedge PA, Gavde S, Joshi MG, et al. Comprehensive cytotoxicity studies of superparamagnetic iron oxide nanoparticles. Biochem Biophys Rep. 2018;13:63–72.

PubMed PubMed Central Google Scholar

55. Singh N, Jenkins GJ, Asadi R, Doak SH. Potential toxicity of superparamagnetic iron oxide nanoparticles (SPION). Nano Reviews. 2010;1(1):53–8.

Article Google Scholar

56. Radović M, Calatayud MP, Goya GF, Ibarra MR, Antić B, Spasojević V, et al. Preparation and in vivo evaluation of multifunctional 90Y-labeled magnetic nanoparticles designed for cancer therapy. J Biomedical Mater Res Part A. 2015;103(1):126–34.

Article Google Scholar

57. Mokhodoeva O, Vlk M, Nykl E, Kukleva E, Suchánková P, Stamberg K et al. Study of 223Ra uptake mechanism by Fe3O4 nanoparticles: towards new prospective theranostic spions. J Nanopart Res. 2016;18.

58. Gawęda W, Pruszyński M, Cędrowska E, Rodak M, Majkowska-Pilip A, Gaweł D, et al. Trastuzumab modified barium ferrite magnetic nanoparticles labeled with radium-223: a new potential radiobioconjugate for alpha radioimmunotherapy. Nanomaterials. 2020;10(10):2067.

Article PubMed PubMed Central Google Scholar

59. Cędrowska E, Pruszyński M, Gawęda W, Żuk M, Krysiński P, Bruchertseifer F, et al. Trastuzumab conjugated superparamagnetic iron oxide nanoparticles labeled with 225AC as a perspective tool for combined α-radioimmunotherapy and magnetic hyperthermia of HER2-positive breast cancer. Molecules. 2020;25(5):1025.

Article PubMed PubMed Central Google Scholar

60. Anitha K, Chenchula S, Surendran V, Shvetank B, Ravula P, Milan R, et al. Advancing cancer theranostics through biomimetics: a comprehensive review. Heliyon. 2024.

https://doi.org/10.1016/j.heliyon.2024.e27692.

Article PubMed PubMed Central Google Scholar

61. Zarepour A, Zarrabi A, Khosravi A, Zarepour A, Zarrabi A, Khosravi A. Spions as nano-theranostics agents: Springer; 2017.

62. Anijdan SM, Gholami A, Lahooti A. Development of radiolabeled dextran coated iron oxide nanoparticles with ^{111}In and its biodistribution studies. Int J Radiation Res. 2020;18(3):539–47.

Google Scholar

63. Gholami A, Anijdan SHM. Development of 153Sm-DTPA-SPION as a theranostic dual contrast agents in SPECT/MRI. Iran J Basic Med Sci. 2016;19(10):1056.

PubMed PubMed Central Google Scholar

64. Shanehsazzadeh S, Grüttner C, Yousefnia H, Lahooti A, Gholami A, Nosrati S, et al. Development of ^{177}Lu-DTPA-SPIO conjugates for potential use as a dual contrast SPECT/MRI imaging agent. Radiochim Acta. 2016;104(5):337–44.

Article CAS Google Scholar

65. Stephen ZR. Magnetic Nanoparticles for Targeted Cancer Theranostics. 2016.

66. Wang L, Shi Y, Jiang J, Li C, Zhang H, Zhang X, et al. Micro-nanocarriers based drug delivery technology for blood-brain barrier crossing and brain tumor targeting therapy. Small. 2022;18(45): 2203678.

Article CAS Google Scholar

67. Carter TJ, Agliardi G, Lin FY, Ellis M, Jones C, Robson M, et al. Potential of magnetic hyperthermia to stimulate localized immune activation. Small. 2021;17(14): 2005241.

Article CAS Google Scholar

68. Gordon MR, Zhuang J, Ventura J, Li L, Raghupathi K, Thayumanavan S. Biodistribution analysis of NIR-labeled nanogels using in vivo FMT imaging in triple negative human mammary carcinoma models. Mol Pharm. 2018;15(3):1180–91.

Article CAS PubMed PubMed Central Google Scholar

69. Gawęda W, Osial M, Żuk M, Pękała M, Bilewicz A, Krysinski P. Lanthanide-doped spions bioconjugation with trastuzumab for potential multimodal anticancer activity and magnetic hyperthermia. Nanomaterials. 2020;10(2):288.

Article PubMed PubMed Central Google Scholar

70. Ejigah V, Owoseni O, Bataille-Backer P, Ogundipe OD, Fisusi FA, Adesina SK. Approaches to improve macromolecule and nanoparticle accumulation in the tumor microenvironment by the enhanced permeability and retention effect. Polymers. 2022;14(13):2601.

Article CAS PubMed PubMed Central Google Scholar

71. Wu J. The enhanced permeability and retention (EPR) effect: the significance of the concept and methods to enhance its application. J Personalized Med. 2021;11(8):771.

Article Google Scholar

72. Chen C, Jianxian G, Gao Y, Chen L, Cui J, Zeng J, Gao M. Ultrasmall superparamagnetic iron oxide nanoparticles: A next generation contrast agent for magnetic resonance imaging. WIREs Nanomed Nanobiotechnol. 2021;14.

73. Papadopoulou S, Kolokithas-Ntoukas A, Salvanou E-A, Gaitanis A, Xanthopoulos S, Avgoustakis K, et al. Chelator-free/chelator-mediated radiolabeling of colloidally stabilized iron oxide nanoparticles for biomedical imaging. Nanomaterials. 2021;11(7):1677.

Article CAS PubMed PubMed Central Google Scholar

74. Azadbakht B, Afarideh H, Ghannadi-Maragheh M, Bahrami-Samani A, Asgari M. Preparation and evaluation of APTES-PEG coated iron oxide nanoparticles conjugated to rhenium-188 labeled rituximab. Nucl Med Biol. 2017;48:26–30.

Article CAS PubMed Google Scholar

75. Aboushoushah SF. Iron oxide nanoparticles enhancing magnetic resonance imaging: A review of the latest advancements. J Science: Adv Mater Devices. 2025;10(2):100875.

76. Shurin MR, Kirichenko VA, Shurin GV, Lee D, Crane C, Kirichenko AV. Radiomodulating properties of superparamagnetic iron oxide nanoparticle (SPION) agent Ferumoxytol on human monocytes: implications for MRI-Guided liver radiotherapy. Cancers. 2024;16(7):1318.

Article CAS PubMed PubMed Central Google Scholar

77. Hoffman D, Sun M, Yang L, McDonagh PR, Corwin F, Sundaresan G, et al. Intrinsically radiolabelled [(59)Fe]-SPIONs for dual mri/radionuclide detection. Am J Nucl Med Mol Imaging. 2014;4(6):548–60.

PubMed PubMed Central Google Scholar

78. Gholami YH, Yuan H, Wilks MQ, Maschmeyer R, Normandin MD, Josephson L, et al. A radio-nano-platform for T1/T2 dual-mode PET-MR imaging. Int J Nanomedicine. 2020;15:1253–66. https://doi.org/10.2147/IJN.S241971

79. Zhao R, Lan D, Xia B, Dong M, Mu J, Zhao Y. PET-Based Dual-Modal probes for. In Vivo Imaging Small. 2025;21(8):e2409713.

80. Beer A. PET imaging of integrin αVβ3 expression. Theranostics. 2011;1:48.

Article CAS PubMed PubMed Central Google Scholar

81. AtİLa DİNÇEr C, GetİRen B, GÖKalp C, ÇIplak Z, KarakeÇİLİ A, Yildiz N. An anticancer drug loading and release study to ternary GO-Fe3O4-PPy and Fe3O4 @PPy-NGQDs nanocomposites for photothermal chemotherapy. Colloids Surf A. 2022;633:127791.

Article Google Scholar

82. Yang X, Hong H, Grailer JJ, Rowland IJ, Javadi A, Hurley SA, et al. cRGD-functionalized, DOX-conjugated, and 64Cu-labeled superparamagnetic iron oxide nanoparticles for targeted anticancer drug delivery and PET/MR imaging. Biomaterials. 2011;32(17):4151–60.

Article CAS PubMed PubMed Central Google Scholar

83. Fu J, Chen L, Hu J, Yu C, Yin J. Radiolabelled nanomaterials for diagnostic and therapeutic applications in hepatocellular carcinoma and other liver diseases. Precision Med Eng. 2025;2(1):100018.

Article Google Scholar

84. Zhong X, Yan J, Ding X, Su C, Xu Y, Yang M. Recent advances in bioorthogonal click chemistry for enhanced PET and SPECT radiochemistry. Bioconjug Chem. 2023;34(3):457–76.

Article CAS PubMed Google Scholar

85. Ghosal K, Bhattacharyya SK, Mishra V, Zuilhof H. Click chemistry for biofunctional polymers: from observing to steering cell behavior. Chem Rev. 2024;124(23):13216–300.

Article CAS PubMed PubMed Central Google Scholar

86. Asad S, Ahl D, Suárez-López YdC, Erdélyi M, Phillipson M, Teleki A. Click Chemistry-Based bioconjugation of iron oxide nanoparticles. Small. 2025;21(11):2407883.

Article CAS PubMed PubMed Central Google Scholar

87. Cano M, Núñez-Lozano R, Dumont Y, Larpent C, Cueva-Méndez G. Synthesis and characterization of multifunctional superparamagnetic iron oxide nanoparticles (SPION)/C60 nanocomposites assembled by fullerene-amine click chemistry. RSC Adv. 2016;6:70374–82.

88. Natarajan A, Gruettner C, Ivkov R, DeNardo GL, Mirick G, Yuan A, et al. Nanoferrite particle based radioimmunonanoparticles: binding affinity and in vivo pharmacokinetics. Bioconjug Chem. 2008;19(6):1211–8.

Article CAS PubMed PubMed Central Google Scholar

89. Sun N, Wang T, Zhang S. Radionuclide-labelled nanoparticles for cancer combination therapy: a review. J Nanobiotechnol. 2024;22(1):728.

Article CAS Google Scholar

90. Miao Y, Yang T, Yang S, Yang M, Mao C. Protein nanoparticles directed cancer imaging and therapy. Nano Convergence. 2022;9(1):2.

Article CAS PubMed PubMed Central Google Scholar

91. Qu J, Tian Z, Wang Q, Peng S, Luo J-b, Zhou Q-h, Lin J. Surface design and Preparation of multi-functional magnetic nanoparticles for cancer cell targeting, therapy, and imaging. RSC Adv. 2018;8(62):35437–47.

Article CAS PubMed PubMed Central Google Scholar

92. Solar P, González G, Vilos C, Herrera N, Juica N, Moreno M, et al. Multifunctional polymeric nanoparticles doubly loaded with SPION and ceftiofur retain their physical and biological properties. J Nanobiotechnol. 2015;13:1–12.

Article Google Scholar

93. Lyer S, Knopp T, Werner F, Zaloga J, Friedrich R, Trahms L et al. Multifunctional spions for theranostics in cancer. Int J Magn Part Imaging IJMPI. 2018;4(1):5.

94. Zhi D, Yang T, Yang J, Fu S, Zhang S. Targeting strategies for superparamagnetic iron oxide nanoparticles in cancer therapy. Acta Biomater. 2020;102:13–34.

Article CAS PubMed Google Scholar

95. Alvandi M, Shaghaghi Z, Aryafar V, Fariba F, Sanaei Z. The evaluation of left ventricular dyssynchrony in hypertensive patients with a preserved systolic function undergoing gated SPECT myocardial perfusion imaging. Ann Nucl Med. 2019;33:899–906.

Article CAS PubMed Google Scholar

96. Naghshtabrizi B, Alvandi M, Shaghaghi Z, Hadei SK, Fariba F, Moradi M, Rabie MAS. Transient ischemic dilation or transient RV visualization in patients with normal SPECT stress myocardial perfusion imaging: correlation with CT coronary artery calcium scoring and coronary angiography. J Nucl Cardiol. 2022;29(5):2149–56.

Article PubMed Google Scholar

97. Zolata H, Davani FA, Afarideh H. Synthesis, characterization and theranostic evaluation of indium-111 labeled multifunctional superparamagnetic iron oxide nanoparticles. Nucl Med Biol. 2015;42(2):164–70.

Article CAS PubMed Google Scholar

98. Lamb J, Holland JP. Advanced methods for radiolabeling multimodality nanomedicines for SPECT/MRI and PET/MRI. J Nucl Med. 2018;59(3):382–9.

Article CAS PubMed Google Scholar

99. Xu M, Qi Y, Liu G, Song Y, Jiang X, Du B. Size-dependent in vivo transport of nanoparticles: implications for delivery, targeting, and clearance. ACS Nano. 2023;17(21):20825–49.

Article PubMed Google Scholar

100. Lima-Tenorio MK, Pineda EAG, Ahmad NM, Fessi H, Elaissari A. Magnetic nanoparticles: in vivo cancer diagnosis and therapy. Int J Pharm. 2015;493(1–2):313–27.

Article CAS PubMed Google Scholar

101. Tsiapa I, Efthimiadou EK, Fragogeorgi E, Loudos G, Varvarigou AD, Bouziotis P, et al. 99mTc-labeled aminosilane-coated iron oxide nanoparticles for molecular imaging of αvβ3-mediated tumor expression and feasibility for hyperthermia treatment. J Colloid Interface Sci. 2014;433:163–75.

Article CAS PubMed Google Scholar

102. Liang S, Wang Y, Yu J, Zhang C, Xia J, Yin D. Surface modified superparamagnetic iron oxide nanoparticles: as a new carrier for bio-magnetically targeted therapy. J Mater Sci Mater Med. 2007;18:2297–302.

Article CAS PubMed Google Scholar

103. Chen J, Wu H, Han D, Xie C. Using anti-VEGF McAb and magnetic nanoparticles as double-targeting vector for the radioimmunotherapy of liver cancer. Cancer Lett. 2006;231(2):169–75.

Article CAS PubMed Google Scholar

104. Ferro-Flores G, Ocampo-García E, Santos-Cuevas BL, Morales-Avila C, Azorín-Vega E. Multifunctional radiolabeled nanoparticles for targeted therapy. Curr Med Chem. 2014;21(1):124–38.

Article CAS PubMed Google Scholar

105. Natarajan A, Xiong C-Y, Gruettner C, DeNardo GL, DeNardo SJ. Development of multivalent radioimmunonanoparticles for cancer imaging and therapy. Cancer Biother Radiopharm. 2008;23(1):82–91.

CAS PubMed Google Scholar

106. Chen D, Dougherty CA, Yang D, Wu H, Hong H. Radioactive nanomaterials for multimodality imaging. Tomography. 2016;2(1):3–16.

Article PubMed PubMed Central Google Scholar

107. Cheng Z, Al Zaki A, Hui JZ, Muzykantov VR, Tsourkas A. Multifunctional nanoparticles: cost versus benefit of adding targeting and imaging capabilities. Science. 2012;338(6109):903–10.

Article CAS PubMed PubMed Central Google Scholar

108. Hong H, Zhang Y, Sun J, Cai W. Molecular imaging and therapy of cancer with radiolabeled nanoparticles. Nano Today. 2009;4(5):399–413.

Article CAS PubMed PubMed Central Google Scholar

109. Hwang DW, Youn H, Lee DS. Molecular imaging using PET/MRI particle. Open Nucl Med J. 2010;2(1):186–91.

110. Jokerst JV, Gambhir SS. Molecular imaging with theranostic nanoparticles. Acc Chem Res. 2011;44(10):1050–60.

Article CAS PubMed PubMed Central Google Scholar

111. Padmanabhan P, Kumar A, Kumar S, Chaudhary RK, Gulyás B. Nanoparticles in practice for molecular-imaging applications: an overview. Acta Biomater. 2016;41:1–16.

Article CAS PubMed Google Scholar

112. Ansari SR, Suárez-López YdC, Thersleff T, Häggström L, Ericsson T, Katsaros I, et al. Pharmaceutical quality by design approach to develop high-performance nanoparticles for magnetic hyperthermia. ACS Nano. 2024;18(23):15284–302.

Article CAS PubMed PubMed Central Google Scholar

113. Kandasamy G, Soni S, Sushmita K, Veerapu NS, Bose S, Maity D. One-step synthesis of hydrophilic functionalized and cytocompatible superparamagnetic iron oxide nanoparticles (SPIONs) based aqueous ferrofluids for biomedical applications. J Mol Liq. 2019;274:653–63.

Article CAS Google Scholar

114. Yang M, Cheng K, Qi S, Liu H, Jiang Y, Jiang H, et al. Affibody modified and radiolabeled gold–iron oxide hetero-nanostructures for tumor PET, optical and MR imaging. Biomaterials. 2013;34(11):2796–806.

Article CAS PubMed PubMed Central Google Scholar

115. Deri M, Ponnala S, Zeglis B, Pohl G, Dannenberg J, Lewis J, Francesconi L. An alternative chelator for (89)Zr radiopharmaceuticals: radiolabeling and evaluation of 3,4,3-(LI-1,2-HOPO). J Med Chem. 2014;57.

116. Papadopoulou S, Kolokithas-Ntoukas A, Salvanou EA, Gaitanis A, Xanthopoulos S, Avgoustakis K, et al. Chelator-free/chelator-mediated radiolabeling of colloidally stabilized iron oxide nanoparticles for biomedical imaging. Nanomaterials. 2021. https://doi.org/10.3390/nano11071677.

Article PubMed PubMed Central Google Scholar

117. Chow JCL. Nanomaterial-Based molecular imaging in cancer: advances in simulation and AI integration. Biomolecules. 2025;15(3).

118. Aboushoushah SFO. Iron oxide nanoparticles enhancing magnetic resonance imaging: A review of the latest advancements. J Science: Adv Mater Devices. 2025;10(2):100875.

CAS Google Scholar

119. Chen L, Zang F, Wu H, Li J, Xie J, Ma M, et al. Using pegylated magnetic nanoparticles to describe the EPR effect in tumor for predicting therapeutic efficacy of micelle drugs. Nanoscale. 2018;10(4):1788–97.

Article CAS PubMed Google Scholar

120. Saki H, Nazem F, Fariba F, Sheikhsharbafan R. A high intensity interval training (running and swimming) and resistance training intervention on heart rate variability and the selected biochemical factors in boys with type 1 diabetes. Diabetes Res Clin Pract. 2023;204:110915.

Article CAS PubMed Google Scholar

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Ethics declarations

Clinical Trial Number

Not applicable

Consent for Publication

The participants signed consent regarding publishing their data

Ethical Approval

This article does not contain any studies with human or animals performed by any of the authors.

Informed Consent

For this type of study, formal consent is not required and informed consent is not applicable.

Conflict of interest

Zahra Shaghaghi, Sahar Nosrati, Ramin Mansouri, Maryam Alvandi declare that they have no conflict of interest.

Additional information

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