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A Systematic Review of Nanotechnology in Cancer Imaging: Recent advances, Challenges, and Future Directions

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Nanotechnology offers various cancer imaging and therapy options, including early detection, precise diagnosis, tailored therapy, and real-time monitoring. Theranostic systems integrate imaging with therapy, while stimuli-responsive nanoparticles enhance targeting and specificity. Combination treatments like chemotherapy, photothermal, and photodynamic therapy improve treatment outcomes. However, clinical translation challenges persist, such as tumor heterogeneity, off-target effects, low penetration depth, and complicated manufacturing processes. Collaboration among researchers, medical professionals, and regulatory organizations is needed to fully utilize nanotechnology in cancer care. The aim of this systematic review was to comprehensively search the literature to evaluate the recent advances, challenges, and future directions of using nanotechnology in cancer imaging and diagnosis. A comprehensive review of the literature was conducted on nanotechnology applications in cancer imaging. PubMed, Science Direct, and the Cochrane Library were the bibliographic databases searched. The findings show how adaptable nanotechnology is in cancer research, including imaging, diagnostics, immunotherapy, and treatment. Collaboration among researchers, medical professionals, and regulatory organizations is needed to fully utilize nanotechnology in cancer care.

1. Introduction

Recent advances in nanotechnology and molecular imaging have provided new biomedical imaging prospects that hold tremendous promise for facilitating the development of agents that will meet clinical demands for disease staging, stratification, and therapeutic response monitoring (Alsharif et al., 2024; Augustine et al., 2021). Unique optical, magnetic, and

chemical characteristics of materials at the nanoscale enable the development of imaging probes with enhanced contrast, regulated biodistribution, signal amplification and quantification, and higher signal density (Kumar et al., 2019).

In order to review the state of the field and identify challenges to the development of nanoparticle-based cancer imaging probes, the NCI Office of Cancer Nanotechnology Research (OCNR) formed an imaging working group in 2011 that included researchers studying nanoparticle-based cancer imaging (Chapman et al., 2013; Hartshorn et al., 2018). Nanoparticles are an appealing material for biological applications because of their size range of 10 nm to 100 nm and their capacity to have a very big surface area (Khan et al., 2019). The nanoparticles can efficiently infiltrate the targeted tissues and migrate across organs inside the body with ease (Souri et al., 2022).

To use the nanoparticles for diagnostic purposes, they can be coupled with therapeutic molecules to target sick tissues, including cancer cells. Nanoparticles resemble DNA in size and are smaller than blood cells (Al-Thani et al., 2024). Better performance is achieved as a result, and they acquire unique physical, chemical, and optical characteristics that enable their application in the medical area for cancer diagnosis and treatment (Taha et al., 2024). They can also be used to improve traditional techniques in addition to creating new ones. In addition, nanoparticles can act as targeting agents, focusing on certain chemicals within cancer cells to enhance cancer imaging and, ultimately, cancer detection. Nanoparticles have been shown in a number of studies to enhance cancer imaging for better detection (Bai et al., 2020; Taha et al., 2024). In order to accurately diagnose and detect cancer, nanoparticles have been generated, with the primary goal being the synthesis of nanomaterials that are efficient and readily absorbed by malignant tumor cells (Anjum et al., 2021).

Various types of nanoparticles, including magnetic, carbon nanotube, polymeric micelles, and liposomes, have been used in cancer imaging and detection due to their diverse biological uses (Singh & Kumar, 2022). These nanoparticles' special qualities have led to their employment in a number of medicinal applications. Imaging probes with improved contrast, increased sensitivity, regulated biodistribution, and improved spatial imaging in MRI, PET, SPECT, and ultrasound methods may be created mainly by the special chemical, optical, magnetic, and chemical characteristics of nanomaterials (Alrushaid et al., 2023).

Microbubbles are among the several types of nanomaterials that are employed in ultrasound imaging and as molecular imaging agents. One research showed that vascular endothelial growth factor receptor 2 and αvβ3-targeted microbubbles precisely attach to angiogenic tumor blood capillaries when employed for molecular ultrasound imaging (Baetke et al., 2015). Early tumor and cancer identification is still a problem in clinical diagnosis. Creating sophisticated nanomaterials is a potential strategy for early cancer imaging, diagnostics, and detection (Dessale et al., 2022). In addition, metal nanoclusters can be used for the diagnosis and treatment of cancer (Truong et al., 2024; Zare et al., 2023). Additionally, researchers are studying ways to make safe and effective nanoparticles for human consumption as well as ways for reducing the toxicity that nanoparticles cause (Najahi-Missaoui et al., 2020). In addition to discussing the challenges and limitations of using different nanoparticles in therapeutic settings, this study focuses on the most significant nanoparticles used in cancer screening and diagnosis in addition to offering ideas for the advancement of cancer imaging

modalities based on nanoparticles.

2. Methods

A comprehensive review of the literature was conducted on nanotechnology applications in cancer imaging. PubMed, Science Direct, and the Cochrane Library were the bibliographic databases searched using the search strategy and keywords ("nanotechnology" OR "nanoparticles" OR "gold nanoparticles" OR "nanomaterials") AND ("cancer imaging" OR "tumor detection" OR “cancer diagnostics"). The references list of the previous reviews were also searched for relevant studies. The authors gathered and examined relevant information to provide professionals with a practical overview. The following basic information have been identified and discussed: research design, nation, cancer type, nanotechnology used, study objectives, applications, and challenges related to applying various nanotechnologies in cancer imaging.

3. Results

The search strategy retrieved 2700 articles in total, 130 of which were duplicates. Following full text screening, 31 studies were ultimately included in this systematic review after the remaining 2570 articles were filtered by title and abstract, with 2160 being excluded (Figure 1).

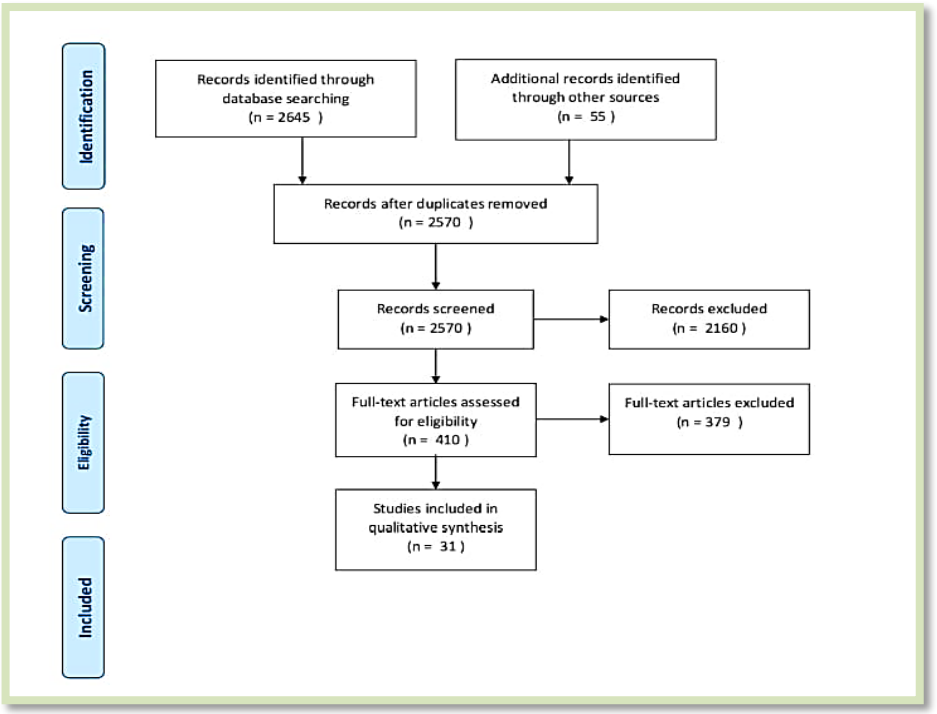

Figure 1: PRISMA flow diagram

The use of nanotechnology in cancer research and therapy is the subject of several studies carried out by various authors, all of which are presented in Table 1. From detection and imaging to treatment, the table demonstrates the broad range of applications of nanotechnology in cancer research. Some research focuses on theranostics, which combines diagnostics with treatment. Chen et al.'s study of liposome nanodrugs for immunotherapy and imaging-guided sonodynamic therapy (SDT) in triple-negative breast cancer (TNBC) is an example.

Table 1: Characteristics of the included studies

First Author	Country	Research Design	Type of Cancer	Nanotechnology Applied	Aim of the study
(Oseledchyk et al., 2017)	USA	Experimental (in vivo)	Ovarian Cancer	Folate-targeted surface-enhanced resonance Raman scattering (SERRS) nanoparticles	To detect microscopic ovarian cancer lesions using SERRS nanoparticles
(Chen et al., 2017)	China	Experimental (in vivo)	Inflammation & Tumors	H_2O_2-responsive liposomal nanoprobe (Lipo@HRP&ABTS)	To detect H2O2 for inflammation imaging and tumor theranostics
(Grippin et al., 2019)	USA	Preclinical study	Cancer (general)	RNA-loaded magnetic liposomes (IO-RNA-NPs)	To develop a nanoparticle for cancer immunotherapy and early prediction of treatment response using MRI.
(Detappe et al., 2017)	USA, France	Preclinical study	Non-small cell lung cancer	Ultrasmall silica-based bismuth gadolinium nanoparticles (SiBiGdNP)	To develop a nanoparticle for dual MRI-CT imaging and radiosensitization in radiation therapy.
(Jo et al., 2017)	USA	In vivo study	Various cancers	SNARF-5F encapsulated polyacrylamide nanoparticles	To develop an in vivo pH mapping nanotechnology for tumor imaging
(Lee et al., 2015)	South Korea	In vitro, ex vivo, and in vivo study	Colon cancer	Theranostic nanoparticles (Au NR@MSS@PNIPAAm) with phototherapeutic and chemotherapeutic agents	To develop a multifunctional endoscope system for colon cancer diagnosis and treatment
(Yuan et al., 2019)	USA	Experimental	Colon Cancer	Furin-mediated intracellular self-assembly of olsalazine nanoparticles (Olsa-NPs)	To enhance tumor retention of imaging agents and anti-cancer drugs
(Mi et al., 2016)	Japan	Experimental	Colon Cancer, Liver Metastasis	PH-sensitive calcium phosphate nanoparticles (PEGMnCaP) with Mn^{2+} ions	To develop a pH-activatable nanoparticle for non-invasive imaging of tumor malignancy
(Chen et al., 2018)	USA	Experimental	HER2+ Breast Cancer	Ultrasmall silica nanoparticles functionalized with anti-HER2 single-chain variable fragments	To design nanoparticles for imaging detection of HER2-overexpressing breast cancer
(Liu et al., 2015)	China	Experimental	Colorectal Cancer	Fe^{3+}-gallic acid coordination polymer nanodots (Fe-CPNDs)	To develop renal clearable nanodots for cancer theranostic applications
(Zhong et al., 2019)	USA	In vivo molecular imaging	Colon cancer	Erbium-based rare-earth nanoparticles (ErNPs) functionalized with anti-PD-L1 antibody	To develop biocompatible NIR-IIb probes for imaging cancer immunotherapy
(Schmutzler et al., 2021)	Germany	In vitro X-ray fluorescence imaging	Prostate cancer	Gold nanoparticles (AuNPs) functionalized with PEGMUA and PSMA-inhibitor	To measure nanoparticle uptake in tumor cells using X-ray fluorescence imaging (XFI)

(Huang et al., 2018)	China	In vitro & in vivo experimental study	Breast cancer	FA-HMME-MNPs-PLGA nanoparticles (FHMP NPs)	To develop a theranostic nanoplatform for photoacoustic imaging-guided sonodynamic therapy (SDT) of breast cancer
(Parchur et al., 2018)	USA	In vivo experimental study	Colorectal cancer liver metastasis (CRLM)	Au@Gd2O3-Ln (Ln = Yb/Er) nanoparticles (TNPs)	To develop a theranostic nanoparticle for image-guided photothermal therapy (PTT) of CRLM
(Chen et al., 2019)	USA	Preclinical Study	Melanoma	Spectrally distinct ultrasmall core-shell silica nanoparticles (C' dots)	To develop image-guided surgical tools for melanoma detection and treatment
(Bakalova et al., 2016)	Japan/Bulgaria	Preclinical Study	Colon Cancer	Hydrogel nanoparticles loaded with QD705 and manganese (QD705@Nanogel and QD705@Mn@Nanogel)	To facilitate passive and electro-assisted delivery of nanoparticles in solid tumors
(Yin et al., 2021)	China	Experimental	Various cancer types (e.g., breast, pancreatic, lung, head & neck, esophageal)	Binary Ratiometric Nanoprobe (BiRN)	To develop a nanotechnology for quantitative imaging of intracellular nanoparticle exposure and predict nanotherapeutic efficacy
(Chai et al., 2024)	China	Invitro	NA	A reversible pH-switchable NIR-II nano-photosensitizer RBT-pH-1 NPs	Develop pH-switchable NIR-II nano-photosensitizer for precise imaging and photodynamic therapy of tumors
(Chen et al., 2024)	China	Invitro/Invivo	Aggressive triple-negative breast cancer	A liposome nanodrug (LP@PFH@HMME) integrating imaging agents and therapeutic agents for bimodal imaging-guided sonodynamic therapy (SDT)	Develop a liposome nanodrug (LP@PFH@HMME) integrating imaging agents and therapeutic agents for bimodal imaging-guided sonodynamic therapy (SDT) is developed, which boosted immunogenicity to enable potent immunotherapy via immune checkpoint blockade (ICB) in TNBC
(Diao et al., 2024)	China	Invitro/Invivo	Cancers	A dual-activatable nano-immunomodulator (DIR NP)	A dual-activatable nano-immunomodulator (DIR NP), which both its photodynamic effect and agonist release can be activated under specific stimuli, is reported for precision cancer photodynamic immunotherapy.
(Gao et al., 2024)	Japan	Invivo	Cancer	Self-Folding Macromolecular Drug Carrier for Cancer Imaging and Therapy	A novel molecular mechanism to augment the relaxation of Nano-sized contrast agents (NCAs) is introduced and demonstrated
(García-Astrain et al., 2024)	Spain	Invitro	Tumor	Scaffold-based three-dimensional (3D) cell models	The implementation of SERS as a dual imaging/sensing tool, to monitor live 3D tumor models over extended periods of time.
(S. Li et al., 2024)	China	Invitro	Lung cancer cells (A549), breast cancer cells (MCF-7), mouse breast cancer cells (4T-1), and cervical cancer cells (HeLa)	Near-infrared methionine-N-Hydroxy succinimide Au nanoclusters (Met-NHs-AuNCs)	A fluorescent probe was synthesized on the basis of Au nanoclusters with near-infrared light emission and applied to fluorescent cancer cell labeling

(W. Li et al., 2024)	China	Invivo/Invitro	Tumor	CXCR4 Receptor-Targeted CuFeSe2 Nano Theranostic Platform	Introduce an "all-in-one" tumor-targeted theranostic platform using CuFeSe2-based composite nanoparticles (CuFeSe2@PA) for magnetic resonance (MR) and computed tomography (CT) dual model imaging-guided hyperthermia tumor ablation.
(Ohannesian et al., 2024)	USA	Invivo	Cancers	Plasmonic nano-aperture label-free imaging of single small extracellular vesicles	Demonstrate the combination of PANORAMA and fluorescence imaging for single sEVanalysis.
(P. Wang et al., 2024)	China	Invivo/Invitro	Breast cancer	A chitosan-camouflaged nanomedicine triggered by hierarchically stimuli	To release drug for multimodal imaging-guided chemotherapy of breast cancer
(Y. Wang, J. Wu, et al., 2024)	China	Invivo	Cancer	Near-infrared-activated and ATP-responsive trifunctional upconversion nano-jelly	To achieve selective recognition of tumor cells and controlled release of drugs. The UCNJs have a NaYF4: Yb, Er core with an outer silica shell with embedded methylene blue (MB)
(Y. Wang, Y. Xu, et al., 2024)	China	Invivo/Invitro	Cervical cancer	Tumor Cell-Targeting and Tumor Microenvironment–Responsive Nanoplatforms for the Multimodal Imaging-Guided Photodynamic/Photothermal/Chemodynamic Treatment of Cervical Cancer	Phototherapy, known for its high selectivity, few side effects, strong controllability, and synergistic enhancement of combined treatments, is widely used in treating diseases like cervical cancer.
(Z. Wang et al., 2024)	China	Invivo/Invitro	Triple-negative breast cancer (TNBC)	"all-in-one" nano-system Au/Cu nanodots/doxorubicin@nanospheres (Au/CuNDs/DOX@NS) with dual-responsive properties	Develop an advanced theranostic platform against TNBC
(Wei et al., 2024)	China	Invivo/Invitro	Triple negative breast cancer	Au-Fe3O4 Janus nanoparticles for imaging-guided near infrared-enhanced ferroptosis therapy	Report a nano-theranostic platform consisting of gold (Au)-iron oxide (Fe3O4) Janus nanoparticles (GION@RGD) that effectively enhances the tumor-specific Fenton reaction through utilization of near-Infrared (NIR) lasers, resulting in the generation of substantial quantities of toxic hydroxyl radicals (•OH).
(Xia et al., 2024)	China	Invivo/Invitro	Tumor	Self-propelled assembly of nanoparticles with self-catalytic regulation for tumour specific imaging and therapy	Report the synthesis of tyrosine (Tyr)-modified peptides capped iodine (I) doped CuS nanoparticles (CuS-I@P1 NPs) as self-catalytic building blocks that undergo self-propelled assembly inside tumour cells via Tyr-Tyr condensation reactions catalyzed by the nanoparticles themselves.

Several types of cancer are covered in the studies, such as cervical, breast, colon, lung, ovarian, melanoma, and ovarian cancer. Specific cancer subtypes, such triple-negative breast cancer and HER2+ breast cancer, are the subject of studies, suggesting a shift toward more individualized and focused cancer therapies.

Quantum dots, silicon-based nanoparticles, magnetic nanoparticles, liposomes, and gold nanoparticles (AuNPs) are examples of novel nanomaterials utilized in cancer research. Each has been adapted to a particular application, such as photothermal treatment, drug administration, or imaging. On the one hand, Au-Fe3O4 Janus nanoparticles are utilized for photothermal treatment and ferroptosis activation in cancer cells, whereas SERRS nanoparticles are utilized for extremely sensitive tumor identification.

As nanotechnology advances from laboratory research to possible therapeutic applications, the included studies contain experimental, preclinical, and clinical trials. Some research focuses on preclinical models, showing how nanotechnology might enhance the effectiveness of cancer treatments. Others investigate therapeutic uses, such enhancing surgical staging and melanoma therapy.

Multiple studies aimed to improve tumor imaging and detection, and integrate imaging and therapy as part of their therapeutic and diagnostic objectives. Among recent developments are multifunctional nanoparticles, which are capable of imaging, medication administration, and treatment, among other purposes. The application of stimuli-responsive nanoparticles, which can react to particular circumstances in the tumor microenvironment to release medications or initiate therapeutic effects, is another new development.

4. Discussion

Clinical applications of nanotechnology in cancer imaging

1. Diverse Applications of Nanotechnology:

The findings show how adaptable nanotechnology is in cancer research, including imaging, diagnostics, immunotherapy, and treatment. A pH-switchable NIR-II photosensitizer was developed by (Chai et al., 2024) for accurate tumor imaging and photodynamic treatment (PDT), and a liposome nanodrug was developed by (Chen et al., 2024) for immunotherapy and image-guided sonodynamic therapy (SDT) in triple-negative breast cancer (TNBC).

2. Innovative nanomaterials and methods:

Gold nanoparticles (AuNPs), liposomes, upconversion nanoparticles (UCNPs), and self-assembling nanoparticles are among the innovative nanomaterials and methods that are highlighted in the study. For tumor-specific imaging and therapy, (Xia et al., 2024) developed self-propelled, tyrosine-modified nanoparticles, while (Wei et al., 2024) employed Au-Fe3O4 Janus nanoparticles for NIR-enhanced Fenton reactions that induced cancer cells ferroptosis.

3. Theranostic Strategies:

Studies concentrated on theranostic platforms, which integrate diagnosis and treatment into one system. Using CuFeSe2-based nanoparticles for magnetic resonance (MR) and computed tomography (CT) imaging-guided hyperthermia tumor ablation, (S. Li et al., 2024) created a

"all-in-one" tumor-targeted theranostic platform. For the treatment of breast cancer, (Y. Wang, J. Wu, et al., 2024) created a multipurpose nanoplatform for photothermal therapy (PTT) and chemotherapy guided by imaging.

4. Stimuli-Responsive Nanotechnology:

Numerous studies highlighted the use of stimuli-responsive nanoparticles, which are triggered by certain factors in the tumor microenvironment, such as enzymes, pH, or temperature. In 2024, Wang et al. produced ATP-responsive upconversion nano-jelly hydrogels for regulated drug release in tumor cells, while (Diao et al., 2024) developed a dual-activatable nanoimmunomodulator (DIR NP) that releases therapeutic drugs in response to tumor-specific stimuli.

5. The use of immunotherapy and immunomodulation:

Investigations examined how nanotechnology could improve immunotherapy and immunological regulation. In TNBC, Chen et al. (2024) showed that their liposome nanodrug might improve immune checkpoint blockade (ICB) treatment, while Diao et al. (2024) revealed that their nanoimmunomodulator could decrease tumor development and promote dendritic cell maturation.

6. Imaging and Diagnostics:

Research aimed to enhance cancer imaging and diagnostics through the application of nanotechnology. Ohannesian et al. employed PANORAMA technology to identify and quantify small extracellular vesicles (sEVs) in cancer patients without the need for labels, while (García-Astrain et al., 2024) created 3D-printed plasmonic scaffolds for real-time tumor evolution sensing and imaging.

The utilization of combination treatments, in which nanotechnology is employed to provide many therapeutic modalities, including chemotherapy, photothermal therapy (PTT), and photodynamic therapy (PDT), is highlighted in several studies. Wang et al. (2024) created a chitosan-camouflaged nanomedicine that treats breast cancer by combining photothermal therapy and chemotherapy, while Wei et al. (2024) employed Au-Fe3O4 Janus nanoparticles for ferroptosis therapy and NIR-enhanced Fenton reactions.

5. Challenges

1. Tumor Heterogeneity and Targeting:

Because tumors vary greatly within and across individuals, it is challenging to create nanoparticles that can consistently target every cancer cell. A near-infrared fluorescent probe, for example, was created by (S. Li et al., 2024) to target the L-type amino acid transporter 1 (LAT1), which is overexpressed in cancer cells. However, the efficacy of the probe in heterogeneous tumors may be limited since not all cancer cells express LAT1. It may be possible to increase imaging coverage and accuracy through the development of multimodal targeting strategies that can target many biomarkers or pathways in tumors simultaneously.

2. Limited Penetration Depth:

The depth of light penetration limits the use of several imaging modalities, including

fluorescence imaging and photodynamic therapy (PDT), particularly in deep-seated cancers. (Chai et al., 2024) developed an NIR-II photosensitizer for deep tissue imaging; yet, in contrast to other imaging modalities such as MRI or CT, the penetration depth of NIR light is still restricted.

This restriction may be addressed by combining nanotechnology with deep-penetrating imaging modalities (such as MRI, CT, or ultrasound). For example, CuFeSe2-based nanoparticles, which provide superior penetration for deep-tissue imaging, were employed by (W. Li et al., 2024) for MR and CT imaging.

3. Off-Target Effects and Toxicity:

Nanoparticles might accumulate in tissues that are not their intended target, which may result in toxicity. (Chen et al., 2018) developed ultra-small silica nanoparticles for HER2+ breast cancer imaging; there is still a concern of off-target accumulation in the kidneys and reticuloendothelial system (RES). By creating renal-clearable nanoparticles(Liu et al., 2015), and improving their biocompatibility and clearance mechanisms, off-target effects may be decreased and safety may be increased.

4. Sensitivity and Specificity:

It is still difficult to get high sensitivity and specificity in cancer imaging, particularly for micrometastases or early-stage cancers. Small extracellular vesicles (sEVs) in cancer patients were detected by (Ohannesian et al., 2024) using PANORAMA technology; however, the sensitivity of sEV-based biomarkers may fluctuate depending on the type of cancer. Enhancing sensitivity and specificity for early cancer diagnosis may be possible by developing multiplexed imaging platforms that can identify many biomarkers concurrently (Chen et al., 2019).

5. Real-Time Imaging and Monitoring:

Real-time monitoring of tumor dynamics, including variations in pH, oxygenation, or medication administration, is not possible with many of the imaging methods available. (Jo et al., 2017) developed nanotechnology for mapping the pH of tumors; nevertheless, it is still difficult to track changes in the tumor microenvironment in real time. Dynamic monitoring of tumor growth and therapy response may be potentially possible by incorporating real-time imaging capabilities into nanoparticles, such as the 3D-printed plasmonic scaffolds for live SERS imaging developed by (García-Astrain et al., 2024).

6. Scalability and Cost:

Scaling up manufacturing for clinical applications is still a major challenge for many nanotechnology-based imaging platforms, which are currently in the experimental or preclinical phases. Upconversion nano-jelly hydrogels, were developed by Wang et al. (2024) for tumor imaging; however, their widespread application may be constrained by their expense and production complexity. Translating these technologies into clinical practice will require lowering costs and streamlining the synthesis and manufacturing processes of nanoparticles.

6. Future directions

1. Platforms for Multimodal Imaging:

More thorough and precise tumor imaging may be possible by integrating many imaging modalities (such as MRI, CT, fluorescence, and photoacoustic imaging) onto a single nano-platform. CuFeSe2-based nanoparticles were created by (W. Li et al., 2024) for MR and CT dual-modal imaging, providing deep tissue penetration and good resolution.

2. Stimuli-Responsive Nanoparticles:

enhancing imaging specificity and minimizing off-target effects may be possible through the development of stimuli-responsive nanoparticles that are triggered by certain circumstances in the tumor microenvironment (such as pH, enzymes, or hypoxia). A dual-activatable nanoimmunomodulator (DIR NP), was developed by (Diao et al., 2024) and releases therapeutic drugs in response to stimuli unique to tumors.

3. Machine learning and artificial intelligence (AI):

Combining AI and machine learning algorithms with imaging based on nanotechnology may improve image interpretation, increase the precision of diagnosis, and allow for real-time tumor dynamics monitoring. complicated imaging data from García-Astrain et al. (2024)'s 3D-printed plasmonic scaffolds for tumor surveillance might be analyzed using AI.

4. Personalized Nano-medicine:

Customizing nanoparticles for each patient according to their genetic profile and tumor biology may enhance the precision of imaging and the effectiveness of treatment. Chen et al. (2024), created a liposome nanodrug for TNBC; however, tailored strategies could increase its efficacy even more.

The development of imaging techniques based on nanotechnology for early cancer detection and screening has the potential to greatly enhance patient outcomes. (Ohannesian et al., 2024) employed PANORAMA technology to detect cancer-specific sEVs early on. This technique has the potential to be further developed into a non-invasive screening tool.

6. Theranostic Nanoparticles:

Increasing the application of theranostic nanoparticles, which integrate therapy and imaging, may enhance therapeutic results and allow for real-time treatment response monitoring. A chitosan-camouflaged nano-medicine for imaging-guided chemotherapy and photothermal treatment was developed by Wang et al. (2024).

7. Improved Biocompatibility and Clearance:

Safety and toxicity might be decreased through the generation of nanoparticles with better biocompatibility and clearance mechanisms (such as renal clearance). As an example, renal-clearable Fe-CPNDs were created by (Liu et al., 2015) for use in cancer imaging and treatment.

7. Conclusion

Nanotechnology provides a wide range of options for cancer imaging and therapy, including

early detection, precise diagnosis, tailored therapy, and real-time monitoring. Theranostic systems integrate imaging with therapy, allowing for image-guided therapy and real-time monitoring. Stimuli-responsive nanoparticles enhance targeting and specificity while minimizing off-target effects. Combination treatments, including as chemotherapy, photothermal therapy, and photodynamic therapy, improve treatment outcomes. However, clinical translation challenges persist, including tumor heterogeneity, off-target effects, low penetration depth, complicated manufacturing processes, and a lack of long-term safety evidence.

Future directions include clinical trials and human research, multimodal and multiplexed imaging, personalized nano-medicine, enhanced biocompatibility and clearance, real-time monitoring and AI integration, scalability and cost-effectiveness, and tackling ethical and regulatory issues. By solving these issues and exploring future avenues such as multimodal imaging, tailored nano-medicine, and AI integration, nanotechnology may be fully utilized to enhance cancer outcomes and lead the way for next-generation cancer diagnostics and therapies. Collaboration among researchers, medical professionals and regulatory organizations is required to realize the full potential of nanotechnology in cancer care. To successfully translate nanotechnology-based imaging and therapy into clinical practice, multimodal imaging platforms must be developed, with a focus on personalized nano-medicine, improved biocompatibility, AI integration, simplified synthesis, and ethical and regulatory issues addressed.

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