Nanotechnology and the Future of Medical Imaging: Enhancing Diagnostic Accuracy

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Abstract

Through medical imaging improvements, nanotechnology implementation enhances diagnostic techniques through better resolution power and improves sensitivity and specificity at the same time. Point-based analysis demonstrates how gold nanoparticles and iron oxide nanoparticles, together with quantum dot nanoparticles as well as polymeric nanoparticles, function as imaging agent enhancers for CT scanners and MR scanners as well as PET scanners and ultrasound scanners, and optical image systems. Higher-resolution imaging at both cellular and molecular levels becomes possible through nanoparticles, which enhances disease detection at an early stage and enables precise identification of abnormalities primarily during cancer diagnosis. Nanoparticle inclusion in theranostic imaging techniques makes it possible to perform battery-powered medical procedures that simultaneously detect and treat diseases, for tailoring precise medical care. Real-time imaging implementations enabled by nanotechnology allow doctors to monitor diseases as they evolve alongside therapeutic responses in patients. Complete realization of nanoparticles within medical imaging demands resolution of biocompatibility and safety issues, along with regulatory requirements. Precision medicine receives significant advancement through nanoparticle-based imaging technologies, which this chapter discusses recent developments alongside existing challenges and future possibilities.

Keywords: Nanoparticles, Medical Imaging, Contrast Agents, Theranostics, Precision Medicine.

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Introduction

Medical imaging serves a fundamental role in cancer diagnosis by helping to locate abnormal areas and direct biopsy procedures and determine disease spread for deciding appropriate treatments between surgery and radiation or chemotherapy. Barentsz et al. (2006) noted that tracking therapy response constitutes a common practice which also functions as a substitute endpoint during drug discovery. Each technique has unique advantages, but they have certain limitations like resolution, sensitivity, and specificity (Wang et al., 2022). Images produced by CT scanners are used to support anomaly diagnosis and other therapeutic assessments. X-rays are generated from different angles using this method, and computers analyze them to create tomographic images (Gallamini et al., 2014). Highly innovative re-created photos have been made by this sophisticated computer-based technology. The skeleton, head, neck, kidney, and bladder can all be diagnosed with CT, which is an efficient method for identifying various tumors. Rapid high-resolution images can be generated with CT scanning (Stock, 2012; Sera, 2021).

PET uses small amounts of radioactive material called radiotracers, which are absorbed by the body and generate positrons, which produce gamma rays when combined with the electrons (Crișan, G et al., 2022). The PET scanner detects these gamma rays and generates an image that can be used to identify cancer. Other metabolic disorders, neurological disorders, and heart disease are also diagnosed with PET scans (Gallamini et al., 2014). Strong magnetic fields and radio waves are used in this non-invasive medical imaging method to create incredibly detailed pictures of the body's internal organs, including soft tissues. It can identify abnormalities such as tumors, blood clots, and soft tissue injuries (Kasban et al., 2015).

High-frequency sound waves are used in ultrasound to create a real image of the body's organs and tissues without the use of ionizing radiation. It is frequently linked to prenatal imaging, which enables medical professionals to track a fetus's growth and development. The heart, blood arteries, pelvis, and abdomen can all be examined by ultrasound (Duck et al., 2020). Medical imaging faces some challenges that impact its efficacy and reliability. The primary issues include resolution limitations, sensitivity concerns, and data management complexities (Haleem et al., 2023). Recent advancements in imaging technologies tackle these issues. However, sophisticated algorithms and processing techniques are required to optimize and improve the imaging modalities (Gull & Parah, 2024).

1.1 Introduction to Nanotechnology in Medical Imaging

Nanotechnology is revolutionizing medical imaging by significantly increasing diagnostic precision and imaging quality. By employing nanoscale materials and technology to improve traditional imaging techniques, this novel approach tackles significant problems in healthcare diagnosis (Han et al., 2019). Gold nanoparticles and quantum dots are examples of nanomaterials made possible by nanotechnology, which has been used to diagnose cancer at the molecular level. Nanomaterials are being utilized in the detection and treatment of cancer (Hanif et al., 2021; Salar et al., 2024). Nanotechnology allows for precise viewing of biological processes and improves imaging quality and diagnostic accuracy through multimodal capabilities, real-time monitoring, and enhanced contrast agents. MRI, CT, PET, and fluorescence imaging are among the techniques whose sensitivity and specificity are improved by improved contrast agents and multimodal imaging (Liu et al., 2023). Early disease detection is facilitated by real-time nanoscale monitoring, which is essential for prompt interventions. Furthermore, nanotechnology facilitates less invasive procedures and tailored medicine, lowering patient risk and improving comfort while enabling accurate, customized diagnosis and treatment planning (Han et al., 2019).

2. Nanotechnology in Medical Imaging

The handling of materials One billion times smaller than a meter at the nanoscale is the focus of nanotechnology, a groundbreaking avenue for scientific advancement. In actuality, nanotechnology refers to any nanoscale technique that has a wide range of practical uses (Hasan et al., 2018). Nanotechnology literally encompasses the development and use of chemical, physical, and biological systems at sizes ranging from single molecules or atoms to submicron dimensions, as well as the integration of the resulting nanomaterials into larger systems. (Nasrollahzadeh et al., 2019). It is well known that nanoparticles are minuscule materials with sizes between 1 and 100nm. To put it more simply, nanoparticles are nano-objects that have three exterior dimensions at the nanoscale. They are frequently divided into many classes according to their characteristics, sizes, or shapes. The different types include metal nanoparticles, ceramic nanoparticles, polymeric nanoparticles, and fullerenes. (Haleem et al., 2023).

2.1 Nanoscale Contrast Agents

Various forms of cancer are detected and diagnosed using medical imaging technologies. Numerous studies have lately focused on the creation of novel nanoparticles as contrast agents for medical imaging that can be used to identify cancer early (Mhlanga et al.,2024). Different types are shown in Figure 1.

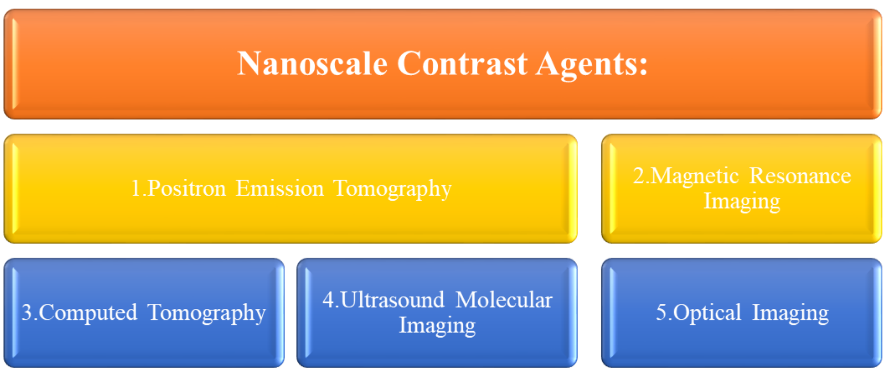

Fig. 1: Nanoscale Contrast Agents: Using Nanoparticles to enhance image contrast and detail.

i. Positron Emission Tomography

The paired 511keV gamma rays produced by the annihilation event of a positron and an electron are intended to be detected by the PET method. Along a line, the annihilation photons go in opposite directions, 180° apart. The target can be surrounded by a PET detector that can prepare signals and transform them into tomographic pictures (Casali et al., 2021).

ii. Magnetic Resonance Imaging

The interaction of nuclei with a nonzero magnetic moment in an external magnetic field is the fundamental basis of magnetic resonance imaging (MRI). Comparably high temporal and spatial resolution, strong tissue contrast, nonionizing radiation, non-invasiveness, and the simultaneous gathering of anatomical and functional data are some of MRI's outstanding qualities (Jiang, M et al., 2021).

iii. Computed Tomography

In medical imaging facilities, CT is a particularly helpful X-ray imaging technique for diagnosing cancer. 2D cross-sectional images of the human body's internal architecture are provided via a CT scan. Consequently, CT can examine translucent tissues, including malignancies. However, CT's capacity to discriminate between adjacent tissues was diminished by a poor signal-to-noise ratio (Mhlanga et al., 2024).

iv. Ultrasound Molecular Imaging

It is a unique modality since it may be used for both therapeutic and imaging applications. Microbubble (MB) is a novel form of contrast agent used in the US modality for diagnostic reasons. MB may improve this modality's sensitivity and specificity for detecting malignancy (Gharat, S. K et al., 2022).

v. Optical Imaging

Through the use of nonionizing radiation, such as visible, ultraviolet, and infrared light, optical imaging noninvasive technique for viewing inside the body, significantly lowers the patient's exposure to dangerous radiation. By stimulating electrons, these kinds of light produce pictures without causing harm that certain other imaging methods that involve ionizing radiation can. (Shahbazi-Gahrouei et al., 2019).

2.2 Enhanced Resolution and Targeting

Nuclear medicine focuses on molecular imaging for noninvasive diagnosis and treatment using radioisotopes, both free and molecule-bound (Woźniak et al., 2022). Recent advances integrate isotope-labeled probes with PET and SPECT, expanding beyond radioactive injections. Nanostructures aid personalized therapies, including hyperthermia, which raises tissue temperature (40-45°C) to enhance cancer treatment (Huang et al., 2024). Superparamagnetic iron oxide nanoparticles (SPIONs) exhibit high magnetic sensitivity without coercivity or remanent magnetization, behaving differently from bulk iron oxide in an alternating magnetic field (Pucci et al., 2022). Effective targeting requires biocompatible stabilizers for colloidal stability and functionalization, binding ligands via electrostatic or chemical interactions (Hu et al., 2023).

2.3 Early Disease Detection

It is essential to discover CNS disorders early because this allows for early therapy, which stops the pathology from getting worse. Unfortunately, because the brain is inaccessible, it is particularly difficult to detect brain-related disorders in their early stages. The absence of diagnostic biomarkers and the decreased blood–brain barrier (BBB) penetration of diagnostic probes is only two of the many drawbacks of the current methods. Furthermore, molecular diagnostic methods cannot replicate real brain activity; they can only identify surrogate endpoint indicators. Numerous Nano diagnostic methods, including contrast-enhanced drugs and imaging probes, have been developed thus far. Probes that are very sensitive and selective with excellent temporal characteristics, tissue penetration, and spatial resolution have been used to study CNS illnesses thanks to recent advancements in diagnostic tests (Hanif et al., 2021).

For the clinical diagnosis of malignancies and neurodegenerative illnesses, a number of imaging modalities are essential, including computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), photoacoustic (PA), and fluorescence (FL) imaging. One of the main forms of brain cancer is GBM Extreme heterogeneity and variation in tumor appearance within the white matter are characteristics of GBM. The molecular mechanisms that cause GBM disease to begin can be identified with the use of emerging molecular techniques (Yang, K et al., 2022). AD is a common neurodegenerative illness that affects several cellular processes and proteins. The amyloid cascade theory is a major focus of the development of AD medications. This hypothesis primarily explains how Aβ monomer self-assembles into insoluble fibrils and soluble oligomers (AβOs), which in turn cause synapse dysfunction and cognitive impairment. Early or progressive loss of neurotraumatic neurons is linked to Parkinson's disease. Currently, imaging and genetic testing are used to diagnose Parkinson's disease (Raj et al., 2021).

3. Types of Nanoparticles and Their Application in Imaging

3.1 There are four different types of nanoparticles as mentioned in Figure 2, and their application is described below.

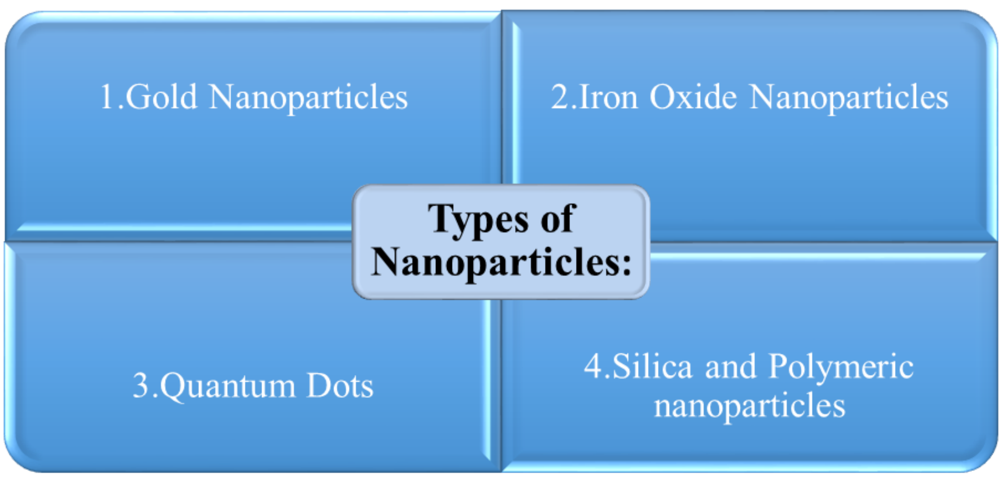

Fig. 2: Types of nanoparticles.

3.2 Gold Nanoparticles (AuNPs)

Much research has been done on gold nanoparticles (AuNPs), which are recognized to have significant medical uses. AuNPs can be created using a variety of techniques, however they can be broadly divided into two categories: chemical and physical synthesis. The half-life of iodinated CT contrast agent in the vasculature is brief. A more robust contrast agent would be very helpful in the domain of intervention techniques grow (Oumano *et al.,* 2021). The feasibility of using gold nanoparticles as a vascular contrast agent for CT that lasts was examined in our study. A modified Turkevich process was employed to create the gold nanoparticles, which were then coated with methoxy-polyethylene glycol-thiol chains and contrasted using a contrast agent based on iodine that was administered to mice. Contrast compounds were examined in vivo by injecting them into the tail vein after being CT-imaged in tubes at 40, 60, and 140kVp (Luo *et al.*, 2021). Two mice were given an iodine-based contrast agent, nine mice were given gold nanoparticles, and one was given saline. Mice were CT-scanned right away at 60kVp, six hours, and twenty-four hours after injection (Jeon et al., 2021). When gold nanoparticles were separated into tubes, their radiographic density was higher than that of an iodine-based contrast agent at 40kVp and was similar in the other CT voltage ranges. Gold nanoparticles in mice produced a strong contrast enhancement that made it possible to see the renal arteries and abdominal aorta clearly, which would not have been possible without a contrast agent (Jiang et al., 2019). This continued until the final time point evaluated, which was 24 hours. Immediately following injection, there was contrast enhancement of the vasculature using a contrast agent based on iodine, but this vanished six hours later (Mahan *et al.*, 2018).

3.3 Iron Oxide Nanoparticles

For a long time, iron oxide nanoparticles (IONP) have been utilized extensively as contrast agents (CA) for magnetic resonance imaging (MRI) because of their exceptional biocompatibility and unique magnetic characteristics (Zhao *et al.*, 2022). One of the most common contrast agents used in magnetic resonance imaging (MRI) in therapeutic settings is based on gadolinium chelates. However, the Food and Drug Administration has repeatedly warned about their possible retention in patients' systems, raising safety concerns, and their toxicity results in serious adverse effects. The benign and biodegradable characteristics of iron oxide nanoparticles (IONPs) makes them a potentially alluring substitute (Jeon *et al.*, 2021).

3.4 Quantum Dots

Over the past twenty years, studies on nanocrystals of fluorescent semiconductor, sometimes referred to as qdots, or quantum dots, has progressed from electrical materials science to medical applications. Vascular endothelial cells will come into direct touch with the quantum dots in the blood when they are utilized as fluorescent probes or drug tracers for in vivo imaging (Xu *et al.,* 2021). Therefore, research into whether quantum dots, when injected into blood arteries as imaging agents, can impact endothelial function is required. Therefore, research into whether quantum dots, when injected into blood arteries as imaging agents, can impact endothelial function is required. We go over the most recent methods for creating, soluble, and functionalizing qdots as well as how they are used in animal and cell biology (Huang *et al.,* 2024). They have recently been used experimentally to use near-infrared emission during surgery to locate lymph nodes in live animals and to track the spread of individual glycine receptors in vivo neurons. Long-term in vivo tracking of cell trafficking, tumor targeting, high-resolution cellular imaging, diagnostics, and the investigation of intracellular functions at the level of individual molecules are all made possible by the new generations of Qdots (Hu *et al.,* 2020).

3.5 Silica and Polymeric nanoparticles

A basic overview of deep learning network architectures is provided for applications involving classification, detection, segmentation, and generation of medical imaging in the most recent deep learning applications to ultrasound imaging (Kasban et al., 2015). After that, A few sample imaging investigations of the unborn head, kidney, liver, thyroid, heart, and breast are examined and summarized, along with ultrasound applications for picture processing and diagnosis. Over time, the use of ultrasound (US) imaging in medicine has grown in acceptance (Avola et al., 2021).

Some important advantages of US technology include its low cost, safety, and ability to give real-time feedback. However, it also has significant disadvantages, like a high degree of noise and poor image quality, which are being addressed by research in this area. Presenting the developments in US medical imaging techniques is the goal of this survey. It tries to arrange the research in this area into three categories: segmentation, classification, and miscellaneous, and describes the studies on the many organs that the US employs the most. This latter category comprises the works that attempt to improve the quality of the obtained US images/volumes or aid during surgical procedures. To the best of our knowledge, this is the first review that examines the many methods used on a wide range of bodily parts (such as the brain, thyroid, heart, breast, fetus, and prostate) in the three subfields of study (Palma-Chavez et al., 2021).

4 Applications of Nanotechnology in Medical Imaging

Figure 3 shows three different applications of nanotechnology in medical imaging.

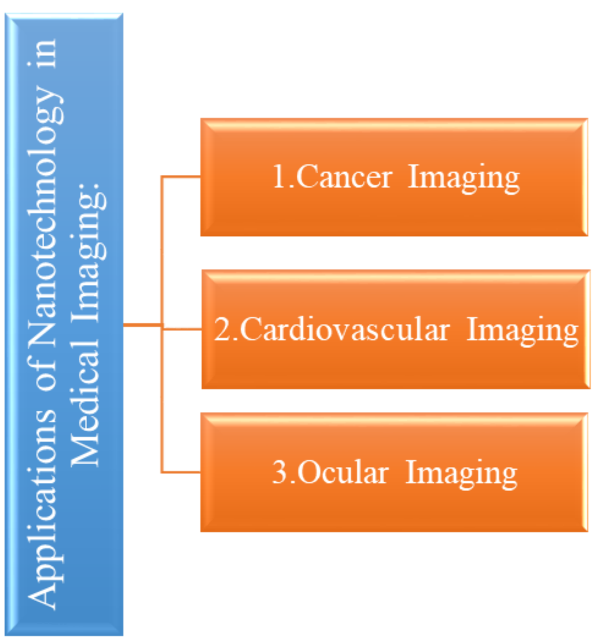

Fig. 3: Application of nanotechnology in medical imaging.

4.1 Cancer imaging

Cancer imaging with nanotechnology focuses on two key areas: (1) nano detection for identifying proteins and cancer cells and (2) nanoparticle-based contrast agents for enhanced imaging. Nanoparticles are being developed for early cancer detection in body fluids, with a focus on capturing circulating tumor cells, though existing methods struggle due to low cell concentrations (Kus-Liśkiewicz et al., 2015). Nanoparticle devices with cancer-specific antibodies or ligands could improve this process. MRI remains a common non-invasive imaging tool, but nanoparticle-based contrast agents offer greater sensitivity and specificity for tumor detection, potentially enabling earlier diagnosis of metastases. However, this approach risks overdiagnosis and overtreatment. For instance, Harsinghani's research showed that nanoparticle-enhanced MRI could upstage cancers by detecting lymph node metastases outside typical resection areas, which, if applied prematurely, could lead to unnecessary tissue removal and increased patient morbidity (Gunasekera *et al.*, 2009).

4.2 Cardiovascular Imaging

Cardiovascular diseases are a leading global cause of death, with myocardial infarction posing challenges for full cardiac regeneration. Stem cell therapy promotes therapeutic angiogenesis, but viral vectors for gene delivery have limitations. Biocompatible nanoparticles (NPs) offer a promising alternative, with liposomes protecting genes and polymers enhancing target specificity (Wang *et al.,* 2021). Chitosan-alginate NPs delivering growth factors have shown improved cardiac function in studies. Additionally, NPs like SPIONs and quantum dots enable long-term stem cell tracking. For hypertension, nanotechnology-based drug delivery systems such as lipid and polymeric nanoparticles offer improved bioavailability and targeted treatment, addressing limitations of conventional antihypertensive medications (Hu *et al.,* 2022).

4.3 Ocular Imaging

Drug delivery through the eye remains difficult because multiple defensive barriers form an intentional challenge, including the tear film and both the ocular surface epithelium and blood-ocular barriers. The delivery of drugs via NPs becomes possible thanks to their small dimensions and customizable surfaces, which enable safe delivery through barriers. Most NPs have a biodegradable composition, which eliminates the requirement for surgical intervention after their drug release operation (Woźniak et al., 2015). Nanotechnology systems help treat cataracts and keratitis, as well as corneal injuries, by both increasing drug penetration intensity and lengthening drug retention durations. Posterior eye disorders, including glaucoma, macular degeneration, and retinoblastoma, usually need interocular injections that produce known adverse effects. Posterior eye drug delivery has become more efficient through Nano-based solutions that combine nanovesicles, Nano implants, NPs, and hydrogels (Pakzad et al., 2020).

5. Innovative Techniques

Allowed by Nano-knocking Nanotechnology has revolutionized medical imaging by enabling innovative techniques that significantly increase diagnostic accuracy and therapeutic results. The key procedure is molecular and functional imaging, displaying Theranostics and real-time imaging. These Nano approaches allowed the transformation of how the disease is diagnosed and monitored, and offer an unprecedented insight into biological functions (Xu et al., 2015).

5.1 Molecular and Functional Display

The molecular display focuses on the visualization of biological processes at the molecular level. Nanoparticles (NP), such as quantum dots and gold nanoparticles, are designed to target specific biomarkers, allowing highly specific display of cellular activities. For example, fluorescent quantum dots provide detailed visualization of tumor edges that help in accurate cancer diagnostics. Functional imaging enhances this ability to quantify dynamic processes such as blood flow or metabolic activity. Molecular and functional applications of nanomaterials have resulted in increased detection of cancer using link gold nanoparticles (Truong *et al.,* 2024). Monitoring neuronal activity of the brain in real time with magnetic nanoparticles. Cardiovascular imaging of nanoparticles based on lipids improved the detection of atherosclerotic plaques (Thakur & Kumar, 2024). The specificity of the Nano-blind molecular display reduces the likelihood of false positives, which is a critical restriction of conventional imaging modalities. Functional imaging supplemented by nanoparticles also increases our understanding of physiological processes under pathological conditions. (Wehn *et al.,* 2024)

5.2 Theranostic Imaging

Theranostic imaging combines diagnostic and therapeutic abilities into a single nanomaterial that makes personalized medicine easier. For example, iron oxide nanoparticles serve two purposes: it acts as contrasting substances to display magnetic resonance imaging (MRI) and add therapeutic agents directly to the destination. This approach is particularly useful in oncology, where real-time monitoring can lead to treatment (Anani *et al.,* 2021). The benefits of theranostic display. Example of benefits of functions: Combined diagnostics and therapy make the treatment of MRI treatment more efficient. Reduced systemic toxicity. Localized therapy minimizes the side effects of targeted chemotherapeutic nanoparticles. Adaptive processing monitors feedback in real time. Theranostic imaging is preparing a way to more efficient and less invasive treatment. By integrating therapeutic delivery with diagnostic feedback, it also reduces the time and cost of clinical intervention (Parashar *et al.,* 2022). Table 1 shows Innovations in Real-Time Imaging.

5.3 Real-time Imaging

Real-time imaging also facilitates minimally invasive diagnostics, where physicians can monitor the success of procedures such as stent placements or tumor ablations in situ.

Table 1: Innovations in Real-Time Imaging

Innovations	Nanomaterial	Use Case	References
Drug Delivery Monitoring	NIR fluorescent nanoparticles	Visualizing drug distribution dynamics	Lee et al., 2021
Organ Transplant Viability	Gold nanorods	Assessing transplant perfusion in real time	Gupta et al., 2022
Metabolic Monitoring	Zinc oxide nanoparticles	Measuring glucose levels continuously	Ahmed et al., 2023

6. Challenges and Future Direction

6.1 Biocompatibility and Safety

Because of their incredibly high surface-to-volume ratio, materials produced as nanoparticles (NPs) have shown distinct behaviors from their bulk counterparts. In general, the cytotoxic impact of nanoparticles increases with their size (Khan et al., 2022). AuNPs have been synthesized and their cytotoxicity evaluated in a variety of forms, including spherical, rod-shaped, triangle-shaped, star-shaped, octahedron-shaped, plate-shaped, and prismatic. Even though nanoparticles have shown great promise in TE applications like improving biological, mechanical, and electrical qualities, having antimicrobial effects, delivering genes, and creating engineered tissues, there are still a lot of obstacles to overcome before they can be widely used in clinical settings (Xu et al., 2021). For instance, there is a strong need for improved instruments and techniques for evaluating the toxicity, carcinogenicity, and teratogenicity of nanoparticles. Second, nanoparticles' toxicity, carcinogenicity, and teratogenicity are all strongly influenced by exposure and dosage (Hasan *et al.,* 2018). The regulatory instruments now in use are not nano-specific; for example, the data requirements for chemical notice, classification criteria, and safety data sheet labeling requirements are still not generally accessible. Biocompatibility and biological safety are typical prerequisites for several beneficial uses of AuNPs (Kus-Liśkiewicz et al., 2021).

6.2 Regulatory and Ethical Concerns

To guarantee patient safety and treatment effectiveness, navigating the clinical approval process necessitates adherence to stringent regulatory criteria. Prolonged schedules, strict data requirements, and intricate approval processes are typical obstacles. Researchers must simplify trial designs, guarantee reliable data collection, and communicate with regulatory bodies early in order to overcome these obstacles (Mehta et al., 2024).

Patient welfare, informed consent, and fair access to therapies must be given top priority in clinical research ethics. Resolving issues like trial bias, data openness, and possible hazards is crucial to preserving public confidence. In order to strike a balance between patient rights and innovation, ethical review boards and continuous ethical evaluations are essential. Researchers can promote more seamless approvals while maintaining ethical integrity in clinical developments by combining regulatory compliance with robust ethical frameworks (Grunwald *et al.*, 2020).

The FDA is the main regulatory body in the US tasked with safeguarding the public's health by making sure pharmaceuticals, biological products, and medical devices are safe, effective, and secure. The regulatory supervision provided by the FDA includes all phases of the product lifecycle, including manufacturing, distribution, post-market surveillance, preclinical research, and clinical trials (Teli et al., 2024). The European Medicines Agency (EMA) is a key player in pharmaceutical regulation throughout the European Union (EU), coordinating the assessment and oversight of pharmaceuticals to guarantee uniform effectiveness, safety, and quality requirements. Based on scientific information provided by manufacturers, the agency's Committee for Medicinal Products for Human Use (CHMP) thoroughly evaluates new medications to make sure that only those that satisfy strict regulatory requirements are authorized for sale (Olawale *et al.,* 2024).

6.3 Improving Targeting Precision and Stability

Since targeted treatments seek to selectively disrupt biological pathways or proteins implicated in the development and spread of cancer, they have emerged as a crucial weapon in the battle against the disease. Monoclonal antibodies and small-molecule inhibitors are two of the most vital instruments in the field of targeted treatment, which focuses on two major areas: angiogenesis and apoptosis. Nanoparticles with targeted alterations have demonstrated greater efficacy and reduced toxicity as compared to non-targeted medicines. A key component of the evolving nanocarrier targeting technique is the EPR effect, which enables nanoparticles to passively target tumors by taking advantage of leaky vasculature and inadequate lymphatic drainage (Chehelgerdi *et al.,* 2023). Maintaining vascular homeostasis, controlling vascular tension, promoting SMC proliferation, and preventing inflammation and thrombosis are only a few of the vital functions performed by vascular endothelial cells. A variety of cell surface proteins, such as P-selectin, vascular cell adhesion molecule-1 (VCAM-1), intercellular cell adhesion molecule-1 (ICAM-1), and platelet endothelial cell adhesion molecule-1 (PECAM-1) are also upregulated as a result of the activation. Endothelial cells and their cell adhesion molecules have been thoroughly investigated as essential drug-delivery targets to prevent or reduce the progression of atherosclerosis since endothelial dysfunction is the first stage of the disease (Zhao et al., 2022).

Conclusion

The integration of nanotechnology into medical imaging has significantly advanced diagnostic precision, therapeutic monitoring, and early disease detection. Nanoparticles, including gold, iron oxide, and quantum dots, have improved imaging contrast, resolution, and targeting at cellular and molecular levels. These innovations enhance imaging modalities such as MRI, CT, PET, and ultrasound, enabling real-time visualization and theranostic applications. In cancer, cardiovascular, and ocular imaging, nanotechnology has improved disease detection, targeted drug delivery, and treatment monitoring. However, challenges such as biocompatibility, regulatory hurdles, and ethical concerns must be addressed for widespread clinical adoption. Ensuring nanoparticle stability, optimizing targeting precision, and refining safety assessments are crucial for future advancements. Despite these challenges, nanotechnology continues to revolutionize medical imaging, providing non-invasive, highly sensitive, and patient-specific diagnostic and therapeutic solutions. As research progresses, nanotechnology-driven imaging will play an increasingly vital role in precision medicine, improving healthcare outcomes and advancing early disease intervention strategies.

References

Anani, T., Rahmati, S., Sultana, N., & David, A. E. (2021). MRI-traceable theranostic nanoparticles for targeted cancer treatment. *Theranostics, 11*(2), 579.

Avola, D., Cinque, L., Fagioli, A., Foresti G., & Mecca, A. (2021). Ultrasound medical imaging techniques: A survey. *ACM Computing Surveys (CSUR), 54,*1-38.

Barentsz, J., Takahashi, S., Oyen, W., Mus, R., De Mulder, P., Reznek, R., Oudkerk, M., & Mali, W. (2006). Commonly used imaging techniques for diagnosis and staging. *Journal of Clinical Oncology, 24*(20), 3234-3244.

Casali, M., Lauri, C., Altini, C., Bertagna, F., Cassarino, G., Cistaro, A., & Signore, A. (2021). State of the art of 18F-FDG PET/CT application in inflammation and infection: a guide for image acquisition and interpretation. *Clinical and Translational Imaging, 9*(4), 299-339.

Chehelgerdi, M., Chehelgerdi, M., Allela, O. Q. B., Pecho, R. D. C., Jayasankar, N., Rao, D.P., Thamaraikani, T., Vasanthan, M., Viktor, P., Lakshmaiya, N., &Saadh, M.J. (2023). Progressing nanotechnology to improve targeted cancer treatment: Overcoming hurdles in its clinical implementation. *Molecular Cancer, 22,*169.

Crișan, G., Moldovean-Cioroianu, N. S., Timaru, D. G., Andrieș, G., Căinap, C., &Chiș, V. (2022). Radiopharmaceuticals for PET and SPECT

imaging: a literature review over the last decade. *International Journal of Molecular Sciences*, *23*(9), 5023.
Duck, F. A., Baker, A. C., &Starritt, H. C. (2020). Ultrasound in medicine. *CRC Press*.
Gallamini, A., Zwarthoed, C., &Borra, A. (2014). Positron emission tomography (PET) in oncology. *Cancers*, *6*(4), 1821-1889.
Gharat, S. K., Godiyal, S. C., Malusare, P. P., Jadhav, K. R., & Kadam, V. J. (2022). Microbubbles contrast agents: general overview as diagnostics and therapeutic agent. *Current Drug Targets*, *23*(10), 960-977.
Grunwald, A. (2020). Nanotechnology-A new field of ethical inquiry? In *The Ethics of Nanotechnology, Geoengineering, and Clean Energy* (pp. 17-31). Routledge.
Gull, S., &Parah, S. A. (2024). Advances in medical image watermarking: A state-of-the-art review. *Multimedia Tools and Applications*, *83*(1), 1407-1447.
Haleem, A., Javaid, M., Singh, R. P., Rab, S., &Suman, R. (2023). Applications of nanotechnology in medical field: A brief review. *Global Health Journal*, *7*, 70-77.
Han, X., Xu, K., Taratula, O., & Farsad, K. (2019). Applications of nanoparticles in biomedical imaging. *Nanoscale*, *11*(3), 799-819.
Hanif, S., Muhammad, P., Niu, Z., Ismail, M., Morsch, M., Zhang, X., Li, M. & Shi, B. (2021). Nanotechnology-based strategies for early diagnosis of central nervous system disorders. *Advanced NanoBiomed Research, 1(10),* 2100008.
Hasan, A., Morshed, M., Memic, A., Hassan, S., Webster, T.J., & Marei, H.E.S. (2018). Nanoparticles in tissue engineering: Applications, challenges and prospects. *International Journal of Nanomedicine*, 5637-5655.
Hu, Q., Fang, Z., Ge, J., & Li, H. (2022). Nanotechnology for cardiovascular diseases. *The Innovation*, *3*(2).
Hu, X., Jia, X., Zhang, K., Lo, T. W., Fan, Y., Liu, D., Wen, J., Yong, H., Rahmani, M., Zhang, L., & Lei, D. (2023). Deep-learning-augmented microscopy for super-resolution imaging of nanoparticles. *Optics Express, 32,*879-890.
Hu, Y., Yang, Z., Lu, X., Guo, J., Cheng, R., Zhu, L., Wang C. F., & Chen, S. (2020). Facile synthesis of red dual-emissive carbon dots for ratiometric fluorescence sensing and cellular imaging. *Nanoscale, 12,* 5494-5500.
Huang, S., &Huang, G. (2024). The utilization of quantum dot labeling as a burgeoning technique in the field of biological imaging. *RSC Advances*, *14*, 20884-20897.
Jeon, M., Halbert, M.V., Stephen Z.R., & Zhang, M. (2021). Iron oxide nanoparticles as T1 contrast agents for magnetic resonance imaging: Fundamentals, challenges, applications, and prospectives. *Advanced Materials, 33,* 1906539.
Jiang, M., Bian, J., Li, Q., Wu, Z., Su, H., Xu, M., & Peng, X. (2021). Zero-to ultralow-field nuclear magnetic resonance and its applications. *Fundamental Research*, *1*(1), 68-84.
Jiang, Q., Liu, Y., Guo, R., Yao, X., Sung, S., Pang, Z., & Yang, W. (2019). Erythrocyte-cancer hybrid membrane-camouflaged melanin nanoparticles for enhancing photothermal therapy efficacy in tumors. *Biomaterials, 192*,292-308.
Kasban, H., El-Bendary, M. A. M., &Salama, D. H. (2015). A comparative study of medical imaging techniques. International *Journal of Information Science and Intelligent System*, *4*(2), 37-58.
Khan, Y., Sadia, H., Ali Shah, S. Z., Khan, M. N., Shah, A. A., Ullah, N., & Khan, M. I. (2022). Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review. *Catalysts*, *12*(11), 1386.
Kus-Liśkiewicz, M., Fickers, P., & Ben Tahar, I. (2021). Biocompatibility and cytotoxicity of gold nanoparticles: Recent advances in methodologies and regulations. *International Journal of Molecular Sciences. 22*, 10952.
Liu, H., Pietersz, G., Peter K., & Wang X. (2022). Nanobiotechnology approaches for cardiovascular diseases: site-specific targeting of drugs and nanoparticles for atherothrombosis. *Journal of Nanobiotechnology, 20,* 75.
Liu, R., Xu, Y., Zhang, N., Qu, S., Zeng, W., Li, R., & Dai, Z. (2023). Nanotechnology for enhancing medical imaging. In *Nanomedicine*, *Springer*, 99-156.
Luo, D., Wang, X., Burda, C., &Basilion, J.P. (2021). Recent development of gold nanoparticles as contrast agents for cancer diagnosis. *Cancers, 13,* 1825.
Mahan, M.M. & Doiron, A.L. (2018). Gold nanoparticles as X-ray, CT, and multimodal imaging contrast agents: Formulation, targeting, and methodology. *Journal of nanomaterials*, *2018*, 5837276.
Mehta, N., Shetty, S., Prajapati, B. G., & Shetty, S. (2024). Regulatory and ethical concerns in the use of nanomaterials. In *Alzheimer's Disease and Advanced Drug Delivery Strategies* (pp. 197-212). Academic Press.
Mhlanga, N., Mphuthi, N., Van der Walt, H., Nyembe, S., Mokhena, T., &Sikhwivhilu, L. (2024). Nanostructures and nanoparticles as medical diagnostic imaging contrast agents: A review. *Materials Today Chemistry*, *40*, 102233.
Nasrollahzadeh, M., Sajadi, S.M., Sajjadi, M., &Issaabadi, Z. (2019). An introduction to nanotechnology. *In Interface science and technology28*,1-27.
Oumano, M., Russell, L., Salehjahromi, M., Shanshan, L., Sinha, N., Ngwa W., & Yu, H. (2021). CT imaging of gold nanoparticles in a human-sized phantom. *Journal of Applied Clinical Medical Physics, 22,*337-342.
Pakzad, Y., Fathi, M., Omidi, Y., Zamanian, A., &Mozafari, M. (2020). Nanotechnology for ocular and optic drug delivery and targeting. In *Nanoengineered Biomaterials for Advanced Drug Delivery* (pp. 499-523). Elsevier.
Palma-Chavez, J., Pfefer, T. J., Agrawal, A., Jokerst, J. V., & Vogt, W.C. (2021). Review of consensus test methods in medical imaging and current practices in photoacoustic image quality assessment. *Journal of Biomedical Optics, 26,* 090901-090901.
Parashar, A. K., Patel, P., Kaurav, M., Yadav, K., Singh, D., Gupta, G. D., &Kurmi, B. D. (2022). Nanomaterials as Diagnostic Tools and Carriers. *Nanoparticles and Nanocarriers Based Pharmaceutical Formulations*, 126.
Pucci, C., Degl'Innocenti, A., Gümüş, M.B., &Ciofani, G. (2022). Superparamagnetic iron oxide nanoparticles for magnetic hyperthermia: Recent advancements, molecular effects, and future directions in the omics era. *Biomaterials Science, 10,* 2103-2121.
Raj, S., Khurana, S., Choudhari, R., Kesari, K. K., Kamal, M. A., Garg, N., Ruokolainen, J., Das, B. C. & Kumar, D. (2021). Specific targeting

cancer cells with nanoparticles and drug delivery in cancer therapy. *In Seminars in Cancer Biology*, *69,*166-177.

Salar, M.Z., Ghaffar, R., Ali, M.R., Mustafa, G., Farooq, A. & Ghafoor, N. (2024). Beyond Traditional Treatments: Nanoparticles in Cancer Therapy. In: V.G.G, Rubio, A. Khan, S. Altaf, Z. Saeed & W. Qamar (Eds.), Complementary and Alternative Medicine (pp: 307-314). Nanotechnology-I. Unique Scientific Publishers, Faisalabad, Pakistan.

Sera, T. (2021). Computed tomography. *Transparency in Biology: Making the Invisible Visible*, 167-187.

Shahbazi-Gahrouei, D., Khaniabadi, P.M., Khaniabadi, B.M., &Shahbazi-Gahrouei S. (2019). Medical imaging modalities using nanoprobes for cancer diagnosis: A literature review on recent findings. *Journal of Research in Medical Sciences 24*, 1-38.

Stock, S. R. (2012). Developments in X-Ray Tomography VIII. *SPIE,8506,* 850601-1.

Teli, M. S., Jhawat, V., & Sharma, A. K. (2024). Development of a Comprehensive Regulatory Model for Medical Devices. *BIO Integration*, *5*(1), 972.

Thakur, A., & Kumar, A. (2024). Cardiovascular Toxicity of Nanoparticles. *Nanoparticle Toxicity and Compatibility*, *161*, 83-121.

Truong, T. T., Mondal, S., Doan, V. H. M., Tak, S., Choi, J., Oh, H., & Oh, J. (2024). Precision-engineered metal and metal-oxide nanoparticles for biomedical imaging and healthcare applications. *Advances in Colloid and Interface Science*, 103263.

Wang, D. K., Rahimi, M., &Filgueira, C. S. (2021). Nanotechnology applications for cardiovascular disease treatment: Current and future perspectives. *Nanomedicine: Nanotechnology, Biology and Medicine*, *34*, 102387.

Wang, Y., Zhang, H., & Xia, S. (2022). Conventional Imaging Techniques. In *Radiology of Infectious and Inflammatory Diseases-Volume 2: Head and Neck,* 3-18.

Wehn, A. C., Krestel, E., Harapan, B. N., Klymchenko, A., Plesnila, N., &Khalin, I. (2024). To see or not to see: In vivo nanocarrier detection methods in the brain and their challenges. *Journal of Controlled Release*, *371*, 216-236.

Woźniak, M., Płoska, A., Siekierzycka, A., Dobrucki, L.W., Kalinowski, L., &Dobrucki, I.T. (2022). Molecular imaging and nanotechnology-emerging tools in diagnostics and therapy. *International Journal of Molecular Sciences, 23,* 2658.

Xu, Q., Gao, J., Wang, S., Wang, Y., Liu, D., & Wang, J. (2021). Quantum dots in cell imaging and their safety issues. Journal of Materials Chemistry *B*, *9*, 5765-5779.

Yang, K., Wu, Z., Zhang, H., Zhang, N., Wu, W., Wang, Z., & Cheng, Q. (2022). Glioma targeted therapy: insight into future of molecular approaches. *Molecular Cancer*, *21*(1), 39.

Zhao, Z., Li, M., Zeng, J., Huo, L., Liu, K., Wei, R., Ni, K., &Gao, L. (2022). Recent advances in engineering iron oxide nanoparticles for effective magnetic resonance imaging. *Bioactive Materials, 12,*214-245.