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Review Article

Nanomaterials in Medical Imaging: Breakthroughs, Challenges, and Prospects

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Nanomaterials have emerged as transformative agents in medical imaging by offering enhanced contrast, improved sensitivity, and multifunctionality. Their unique physicochemical properties enable superior performance in various imaging modalities, including MRI, CT, PET, SPECT. Recent advancements in nanotechnology have led to the development of targeted imaging agents with high specificity, enabling early disease detection and precision diagnostics. Real-time imaging and theranostics, especially in oncology and neurology, are made possible by advancements in smart and stimuli-responsive nanoplatforms. Despite these breakthroughs, challenges such as biocompatibility, toxicity, stability, and regulatory hurdles remain significant obstacles to clinical translation. This paper explores the latest advancements in nanomaterials for medical imaging, highlighting their state-of-the-art applications, ongoing challenges, and prospects. The integration of nanotechnology with artificial intelligence and personalized medicine is expected to further revolutionize the field, paving the way for next-generation potent diagnostic tools that improve patient outcomes and enhance the accuracy of medical imaging techniques.

Introduction

Medical imaging is an essential tool in modern healthcare for accurate disease diagnosis, treatment planning, and real-time monitoring of therapeutic outcomes [1]. Over the past decades, imaging technologies such as X-ray, ultrasound imaging, computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET) have significantly advanced (figure 1) [2, 3]. However, conventional imaging agents often suffer from limitations such as poor biocompatibility, low resolution, inadequate contrast resolution, and limited specificity for disease markers. By overcoming these obstacles and providing special optical, magnetic, and structural qualities, nanomaterials have completely changed medical imaging [4].

Nanomaterials, characterized by their nanoscale dimensions, exhibit enhanced physical and chemical attributes, including high surface-to-volume ratio, tunable optical properties, and targeted delivery potential. These properties enable nanomaterials to function as highly efficient contrast agents, offering improved imaging sensitivity, resolution, and multifunctionality [5]. For instance, quantum dots (QDs) have shown exceptional fluorescence properties for optical imaging, while magnetic nanoparticles (MNPs) have been extensively employed in MRI to enhance contrast and provide functional imaging capabilities [6]. Furthermore, nanomaterials have facilitated the integration of multimodal imaging techniques, allowing for a comprehensive diagnostic approach by combining different imaging modalities such as PET-MRI or fluorescence-photoacoustic imaging. Such hybrid imaging strategies enhance diagnostic precision by leveraging the strengths of each modality while compensating for their individual limitations [7]. Additionally, surface modifications and functionalization of nanomaterials have enabled targeted imaging, wherein nanoparticles are designed to bind specifically to disease biomarkers, thereby improving specificity in disease detection [8].

Despite the promising potential of nanomaterials in medical imaging, several challenges remain to be addressed. Issues such as toxicity, long-term biocompatibility, scalability, and regulatory concerns pose significant barriers to clinical translation [9]. Moreover, the cost-effective synthesis and large-scale production of nanomaterials for widespread medical use require further advancements in material engineering and manufacturing techniques.

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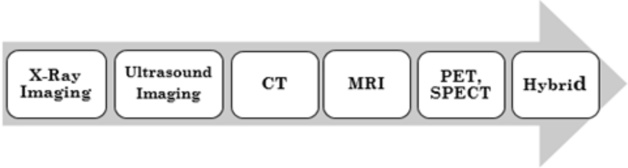

Figure 1: Generation of medical imaging modality

This manuscript provides a comprehensive review of the breakthroughs in nanomaterials for medical imaging, highlighting their applications across various imaging modalities, associated challenges, and prospects. By addressing current limitations and exploring emerging trends, this review aims to provide insights into the evolving landscape of nanotechnology-driven medical imaging and its potential impact on the future of diagnostics and precision medicine.

Types of Nanomaterials for Medical Imaging

Nanomaterials can be classified based on their composition and imaging functionality. The categories below outline the principal nanomaterials employed in medical imaging applications [10] (figure 2).

Quantum Dots (QDs): Semiconductor nanoparticles with high fluorescence efficiency for optical imaging. Quantum dots are semiconductor nanocrystals that exhibit unique fluorescence properties, making them highly effective for optical imaging [11]. Their high quantum yield, photostability, and tunable emission spectra enable precise imaging of biological structures at the cellular and molecular levels. QDs have been extensively explored for fluorescence-guided surgery, in vivo imaging, and cancer diagnostics.

Gold Nanoparticles (AuNPs): Used in photoacoustic and X-ray imaging due to their excellent X-ray attenuation properties. Gold nanoparticles possess excellent X-ray attenuation properties, making them suitable contrast agents for computed tomography (CT) imaging [12]. Additionally, their strong plasmonic resonance allows for applications in photoacoustic imaging and surface-enhanced Raman spectroscopy (SERS)-based imaging. Functionalization of gold nanoparticles with targeting ligands enhances their specificity for diseased tissues.

Magnetic Nanoparticles (MNPs): Primarily iron oxide-based nanoparticles are widely used as MRI contrast agents. They enhance T1 and T2-weighted MRI signals, improving imaging resolution and diagnostic accuracy. These nanoparticles can also be functionalized with biomolecules for targeted imaging of tumors and inflammatory diseases [13].

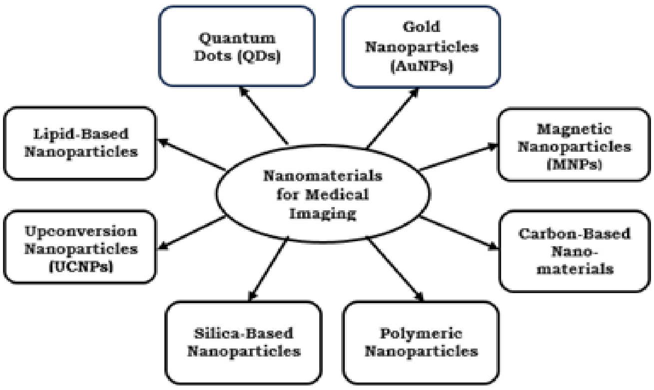

Figure 2: Important types of nanomaterials for medical imaging

Carbon-Based Nanomaterials: Carbon nanomaterials, including graphene oxide, carbon dots, and carbon nanotubes, have gained attention for their fluorescence and photothermal properties [14]. Carbon dots exhibit strong fluorescence emission, making them promising candidates for bioimaging applications. Graphene-based nanomaterials are also explored for multimodal imaging approaches.

Polymeric Nanoparticles: Polymeric nanoparticles serve as versatile carriers for both imaging agents and therapeutics, enabling simultaneous imaging and drug delivery (theragnostic) [15]. These biocompatible nanomaterials can be engineered for targeted imaging applications, particularly in molecular imaging and functional imaging techniques.

Silica-Based Nanoparticles: Mesoporous silica nanoparticles are extensively used for fluorescence and multimodal imaging applications. Their high surface area allows for the encapsulation of multiple imaging agents, enhancing imaging contrast and diagnostic capabilities [16].

Upconversion Nanoparticles (UCNPs): UCNPs exhibit unique optical properties by converting near-infrared (NIR) light into visible emission. This feature allows for deep-tissue imaging with minimal photodamage and background autofluorescence, making them ideal for in vivo imaging applications [17].

Lipid-Based Nanoparticles: Liposomes and other lipid-based nanoparticles are widely explored for contrast enhancement in ultrasound imaging and molecular imaging applications. These nanoparticles are biocompatible and can be loaded with imaging probes for targeted delivery [18].

Smart and Stimuli-Responsive Nanoplatforms: Since stimuli-responsive smart polymers can be purposely made to alter their properties under the influence of certain external triggers such as a change in temperature, pH, or light, they are ideally suited for nanoimaging [19]. Such polymers can be used as imaging agents in optical imaging, MRI, or PET when combined with nanoparticles or nanogels to target specific tissues or diseased sites.

Here is a tabulated summary (table 1) of various types of nanomaterials used for medical imaging based on the brief description provided, along with their chemical composition, imaging modality, specific functions, and key functional advantages. These nanomaterials enhance the imaging sensitivity, resolution, and specificity across a range of diagnostic platforms. Here is a succinct table (table 2) summarises the composition, imaging mode, and benefits of the smart and stimuli-responsive nanoplatforms utilised in medical imaging.

Specific Role of Nanomaterials in Medical Imaging

Nanomaterials are set to transform medical imaging by enhancing crucial performance metrics like tissue penetration depth, signal strength, and imaging resolution. Their ability to be adjusted in terms of size, surface chemistry, and physical properties not only improves contrast in multimodal imaging but also opens up exciting possibilities for targeted delivery. For instance, gadolinium-based nanoparticles and superparamagnetic iron oxide nanoparticles (SPIONs) offer T1 and T2 contrast in MRI, respectively. On the other hand, optical imaging uses upconversion nanoparticles and

Table 1: Types of nanomaterials utilized in medical imaging: composition, modalities, specific role and functional advantages

Type of Nanomaterial	Composition	Imaging Modality	Specific Role	Functional Advantages
Quantum Dots (QDs)	Semiconductor nanocrystals (e.g., CdSe, CdTe)	Fluorescence imaging, Optical imaging	Bright fluorescence for long-term cellular and molecular imaging	High brightness, tunable emission, photostability
Gold Nanoparticles (AuNPs)	Gold	CT, Photoacoustic Imaging, Optical Imaging	High X-ray absorption for CT, acoustic signal enhancers, dual-modal imaging	Strong X-ray attenuation, biocompatibility, easy surface modification
Magnetic Nanoparticles (MNPs)	Fe_3O_4 or γ-Fe_2O_3	Magnetic Resonance Imaging (MRI)	Enhance contrast; enable targeted imaging and magnetic targeting; cell tracking	High magnetic susceptibility, long circulation time
Carbon-Based Nanomaterials	Graphitic carbon	Photoacoustic Imaging, Raman Imaging	Deep-tissue imaging, photothermal conversion for theranostics	Strong NIR absorption, high surface area
Polymeric Nanoparticles	Biodegradable polymers (e.g., PLGA, PEG)	Fluorescence, PET, MRI (if labeled)	Act as carriers for contrast agents or drugs; enable theranostics and controlled release	Versatile carrier, controlled release, low toxicity
Silica-Based Nanoparticles	Amorphous SiO_2	Optical Imaging, PET (if doped)	High surface area for functionalization; used for fluorescence labeling and multimodal imaging	Biocompatibility, tunable porosity, easy functionalization
Upconversion Nanoparticles (UCNPs)	Rare-earth-doped crystals (e.g., $NaYF_4$:Yb,Er)	Optical Imaging, Deep-tissue Imaging	Convert NIR to visible light for deep-tissue imaging and dual-modality imaging	Low background fluorescence, deep tissue penetration
Lipid-Based Nanoparticles	Phospholipid bilayer vesicles	MRI, Ultrasound, CT	Biocompatible carriers for contrast agents or drugs; responsive to stimuli like ultrasound	Biocompatibility, can carry multiple agents

quantum dots that deliver strong, stable fluorescence for high-level imaging across the near-infrared spectrum [20]. Bismuth and gold nanoparticles provide more X-ray contrast in CT imaging [21]. Furthermore, nanobubbles and perfluorocarbon droplets improve contrast in ultrasound and assist in image-guided therapy. Photoacoustic imaging benefits from gold nanorods and carbon nanotubes, allowing for deep tissue visualization. Radiolabeled nanoparticles enable precise molecular imaging for PET/SPECT. The advent of hybrid nanomaterials facilitates multimodal imaging (e.g., MRI/CT and PET/optical), which not only improves accuracy of diagnosis but also opens the door for theranostics, integrating imaging and therapy seamlessly [22].

A summary of their functions according to important imaging parameters is provided below in a tabular form (**table 3**).

Applications of Nanomaterials in Medical Imaging

Nanomaterials' distinct optical, magnetic, and structural characteristics at the nanoscale have made them effective instruments in medical imaging [23]. Because of their large surface area, adjustable size, and functionalisation potential, they are perfect for improving image contrast, facilitating targeted imaging, and assisting with multimodal imaging methods. In a variety of imaging modalities, including MRI, CT, PET, ultrasound, and optical imaging, nanomaterials are essential for enhancing early illness detection, real-time monitoring, and image-guided therapy by increasing

Table 2: Smart and stimuli-responsive nanoplatforms for medical imaging

Type of Stimulus	Nanoplatform Composition	Imaging Modality	Advantages
pH-responsive	Poly(L-histidine)-coated iron oxide nanoparticles	MRI	Activates in acidic tumour settings; enhances targeting and contrast
Temperature	PNIPAM-based nanogels with gadolinium chelates	MRI	Tumor-specific activation and contrast enhancement are made possible by thermal sensitivity.
Redox	Disulfide-linked PEG-PLGA nanoparticles with loaded fluorophores	Fluorescence Imaging	Triggers the high GSH environment in tumours and encourages the release of certain signals.
Enzyme	Peptide-cleavable polymer shell on gold nanoparticles	CT / Fluorescence Imaging	Tumor-associated enzymes (like MMPs) activate it; high specificity
Light	Photo-cleavable polymers loaded with NIR dyes	Optical/NIR Imaging	Spatial-temporal control; non-invasive activation with external light
Dual (pH + Enzyme)	Polymeric micelles with dual-labile linkers and imaging agents	MRI / PET / Optical Imaging	Improved accuracy of targeting and multimodal imaging

Table 3: Concise role of nanomaterials in medical imaging w.r.t. imaging resolution, signal strength, and penetration depth

Parameter	Enhanced By	Key Nanomaterials	Impact
Imaging Resolution	Light scattering, magnetic effects, photostability	Quantum dots, AuNPs, SPIONs	Enables clearer detection of small tumors, microvasculature, small lesions and/or early-stage abnormalities with greater precision.
Signal Strength	Relaxivity, contrast enhancement, luminescence	Gd-NPs, SPIONs, UCNPs, AuNPs, BiNPs	Higher signal strength improves the visibility of target tissues with better lesion detectability, and reduced dose requirements.
Imaging Depth	NIR absorbance, reduced scattering	Gold nanorods, Carbon nanotubes, UCNPs, Silica-coated NPs	Enables non-invasive imaging of deep-seated tissues like liver tumors, brain vasculature, and lymph nodes.

sensitivity, resolution, and specificity (figure 3).

Magnetic Resonance Imaging (MRI)

Nanomaterials have significantly improved MRI technology by enhancing contrast, improving specificity, and enabling functional imaging [24]. Key examples of nanomaterials include

Superparamagnetic Iron Oxide Nanoparticles (SPIONs): These nanoparticles improve T2 contrast, allowing for better visualization of tumors, inflammatory sites, and vascular structures [25]. Functionalized SPIONs have been developed for targeted imaging of specific biomarkers.

Gadolinium-Based Nanoparticles: Gadolinium-loaded nanoparticles enhance T1 contrast and provide prolonged circulation time compared to conventional gadolinium-based agents, reducing toxicity concerns [26].

Multifunctional Nanoparticles: Hybrid nanomaterials combining MRI contrast with drug delivery capabilities enable theranostic applications, allowing for simultaneous imaging and therapy [27].

Nanoparticle-Based Smart Contrast Agents: These agents respond to physiological conditions such as pH, enzyme activity, or temperature, providing real-time imaging of disease progression [28]. For example, thermo-responsive polymers (e.g., PNIPAM) can encapsulate contrast agents (e.g, $Gd^{3}z$ chelates) that are released at hyperthermic tumor sites and pH-responsive polymers can release MRI agents in acidic tumor microenvironments.

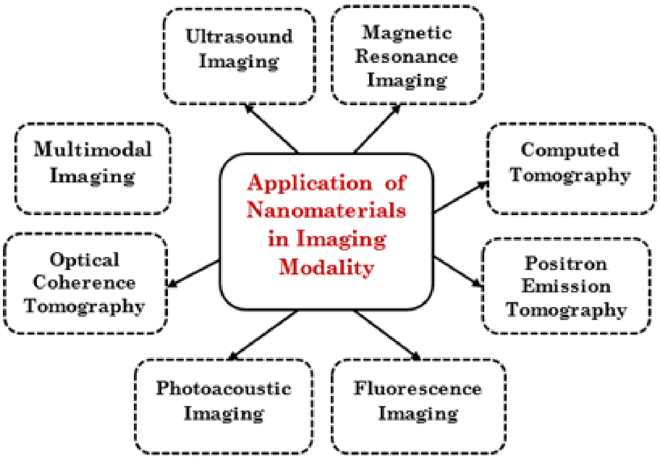

Figure 3: Applications of nanomaterials in different imaging modality

Targeted Imaging: Functionalized nanoparticles conjugated with antibodies or peptides allow for selective imaging of tumors, atherosclerotic plaques, and neurodegenerative diseases [29].

Computed Tomography (CT)

Nanomaterials are revolutionizing computed tomography (CT) imaging by offering improved contrast, higher resolution, and targeted imaging [30]. Among the major nanomaterials are

Gold Nanoparticles (AuNPs): Due to their high X-ray attenuation coefficient, gold nanoparticles serve as superior CT contrast agents, providing enhanced imaging of tumors and vascular structures [31].

Bismuth-Based Nanoparticles: Bismuth nanoparticles offer strong X-ray attenuation with reduced toxicity, making them an effective alternative to iodine-based contrast agents [32].

Hybrid Nanoparticles: Multifunctional nanoparticles combining CT contrast with fluorescence or MRI capabilities enable multimodal imaging [33].

Stimuli-Responsive polymers: Used to increase CT contrast at pathological areas by encapsulating high-Z elements (such as gold and iodine) and releasing them in response to pH or enzyme activity [34].

Targeted Contrast Agents: Surface-modified nanoparticles with antibodies or peptides enhance selective imaging of tumors, infections, and vascular abnormalities [35].

Ultrasound Imaging

By enhancing picture contrast, facilitating targeted administration, and providing intelligent, stimuli-responsive behaviour, nanomaterials have greatly improved ultrasonic (US) imaging [36]. Important nanoparticles applied in ultrasound imaging include

Nanobubbles: Nanobubbles are useful for imaging vascular and tumour tissues because of their powerful echogenic signals, which are produced by a gas core such as nitrogen or perfluoropropane that is encased in a lipid or polymer shell [37].

Nanodroplets: A volatile perfluorocarbon core found in nanodroplets vaporises when heated or subjected to ultrasound, allowing for site-specific, targeted contrast enhancement [38].

Polymeric Nanoparticles: Drug delivery for theranostic applications and ultrasound imaging are made possible by polymeric nanoparticles, which are composed of biocompatible polymers such as PLGA or PEG-PLGA [39].

Gas-generating Nanoparticles: By producing CO, or O, in response to an acidic pH or increased ROS in tumours or inflammatory tissues, gas-generating nanoparticles derived from calcium carbonate, manganese dioxide, or catalase allow for targeted ultrasound imaging by selectively enhancing contrast at sick areas [40].

Ultrasound-sensitive Liposomes: Phospholipid-based vesicles known as ultrasonic-sensitive liposomes react to ultrasound by breaking down, which releases their cargo or improves imaging contrast at the intended location [41].

Gold Nanoparticles (GNPs): Gold nanoparticles are inorganic nanomaterials with a high atomic number that provide strong acoustic enhancement and are also useful in photoacoustic imaging applications [42].

Microbubble-loaded Nanogels: In order to provide regulated and targeted therapy, microbubble-loaded nanogels incorporate microbubbles into a soft hydrogel matrix, improving stability and facilitating ultrasound-triggered drug release [43].

Carbon-based Nanomaterials: Although they are not very echogenic, carbon-based nanomaterials like graphene oxide and carbon dots are useful in multimodal imaging platforms that combine ultrasound with optical or photoacoustic imaging to improve diagnostic capabilities [44].

PET Imaging

Nanomaterials enhance PET imaging by enabling targeted radiotracer delivery, improved contrast, and theranostic applications through functionalization, offering precise, real-time molecular imaging for diseases like cancer [45]. Major nanomaterials employed in PET imaging are as follows

Gold Nanoparticles (AuNPs): These particles are useful in PET for targeted molecular imaging because of their large surface area, biocompatibility, and stable radiolabelling [46].

Iron Oxide Nanoparticles: Dual PET imaging uses superparamagnetic iron oxide nanoparticles labelled with PET isotopes such as v x Ga or v t Cu [47,48]. They are useful for high-resolution neuroimaging and cancer diagnosis because they allow for simultaneous anatomical and functional imaging.

Quantum Dots (QDs): Usually made of semiconductor ingredients like CdSe/ZnS, QDs are employed in PET imaging through surface conjugation with radiolabeling chelators (such as v t Cu, v x Ga). By fusing fluorescence and PET, they make multimodal imaging possible, providing accurate tumour targeting, a steady signal, and great sensitivity [49].

Liposomes: Encapsulating or labelling PET isotopes such as v t Cu or ^{1}x F, liposomes are composed of phospholipid bilayers and are utilised in PET imaging [50]. They offer prolonged circulation, biocompatible, focused delivery, and are perfect for theranostics and tumour imaging [51].

Carbon Nanotubes/ Dots: Functionalised with PET isotopes such as v t Cu or v x Ga, carbon nanotubes and carbon dots are utilised in PET imaging for sensitive tumour identification and targeted delivery [52]. Effective radiolabeling and precise molecular targeting are made possible by their large surface area and adaptable chemistry.

Silica Nanoparticles: Often surface-functionalized and mesoporous, silica nanoparticles are labelled with PET isotopes such as Cu for targeted imaging. For accurate tumour identification in PET, they provide a high loading capacity, biocompatibility, and variable surface chemistry [53].

Polymeric Nanoparticles: Using isotopes like v t Cu or ^{1}x F, polymeric nanoparticles, which are composed of biocompatible materials like PLGA or PEG are employed in PET imaging. They are useful for tumour imaging and theranostic applications because they have regulated release, extended circulation, and the ability to be surface-modified with targeted ligands [54].

Dendrimers: These highly branched polymers, which are labelled with PET isotopes like v t Cu, allow imaging agents to be delivered in a targeted and multivalent manner. In PET imaging, their distinct structure and surface functions improve signal strength and specificity [55].

Smart Polymers: For site-specific imaging, smart polymers can be radiolabeled and engineered to accumulate in response to pH or enzymatic stimuli.

Fluorescence Imaging

Nanomaterials have significantly improved fluorescence imaging by enhancing sensitivity, photostability, and targeted imaging capabilities [56]. For moderate-depth imaging with little autofluorescence, fluorescence imaging in the NIR-I range (700–900 nm) employs dyes such as ICG. Using nanomaterials like carbon nanotubes and quantum dots, NIR-II imaging (1000–1700 nm) provides deeper, high-resolution imaging that is perfect for seeing brain structures, arteries, and tumours [57]. Widely used nanomaterials comprise of

Quantum Dots (QDs): These semiconductor nanoparticles exhibit bright, stable fluorescence, making them ideal for cellular and molecular imaging. QDs enable high-resolution imaging in cancer diagnostics and fluorescence-guided surgery [58].

Carbon Dots (CDs): CDs are biocompatible, photostable, and water-soluble, making them excellent candidates for bioimaging and real-time fluorescence tracking of biological processes [59].

Upconversion Nanoparticles (UCNPs): These nanoparticles convert near-infrared (NIR) light to visible fluorescence, enabling deep-tissue imaging with minimal background auto fluorescence [60].

Gold Nanoclusters (AuNCs): Due to their strong fluorescence and biocompatibility, AuNCs are used for targeted fluorescence imaging and photodynamic therapy [61].

Silica-Based Fluorescent Nanoparticles: These nanoparticles provide stable and tunable fluorescence emission, allowing for long-term cellular tracking and imaging applications [62].

Photoacoustic Imaging

Nanomaterials have significantly enhanced photoacoustic imaging (PAI) by improving contrast, resolution, and targeting capabilities [63]. In NIR-I (700–900 nm), photoacoustic imaging employs gold nanorods and ICG to provide moderately deep tumour and vascular imaging. NIR-II (1000–1700 nm) uses nanomaterials like carbon nanotubes to provide deeper, high-resolution imaging of brain arteries and tumours [64]. Several significant nanomaterials are

Gold Nanoparticles (AuNPs): Their strong surface plasmon resonance allows efficient light absorption and conversion to acoustic signals, making them ideal contrast agents for PAI [65].

Carbon-Based Nanomaterials: Graphene, carbon nanotubes, and carbon dots exhibit strong optical absorption, enabling deep-tissue imaging with high sensitivity [66].

Upconversion Nanoparticles (UCNPs): These nanoparticles provide multimodal imaging capability by combining fluorescence and photoacoustic imaging, improving imaging depth and precision [67].

Silica-Coated Nanoparticles: These allow controlled photothermal effects and improved stability, making them suitable for long-term in vivo imaging applications [68].

Polymeric Nanoparticles: Functionalized polymers with strong optical absorption enhance tumor imaging and vascular imaging applications [69].

Optical Coherence Tomography (OCT)

By providing molecular imaging capabilities and enhancing image contrast and depth, nanomaterials have become potent OCT enhancers [70].

Gold-Based Nanomaterials: Gold nanoparticles, such as nanorods and nanoshells, functionalise their surfaces to allow for targeted imaging and improve OCT contrast through high NIR scattering [71].

Iron Oxide Nanoparticles (SPIONs): With its magnetic characteristics and mild light scattering, iron oxide nanoparticles provide OCT-MRI contrast for imaging [72].

Carbon-Based Nanomaterials: With OCT, deep tissue imaging and photothermal applications are made possible by the high absorbance and scattering of graphene oxide and carbon nanotubes [73].

Quantum Dots (QDs): For simultaneous structural and molecular imaging, hybrid OCT devices incorporate quantum dots, which are primarily utilised in fluorescence imaging [74].

Silica Nanoparticles: Silica nanoparticles are biocompatible, allow surface modification for targeting, boost scattering for higher OCT contrast, and can be coated or doped with metal cores for improved optics [75].

Polymeric Nanoparticles: Theranostic OCT applications that integrate targeted therapy and imaging are made possible by polymeric nanoparticles, which serve as contrast agents and drug carriers [76].

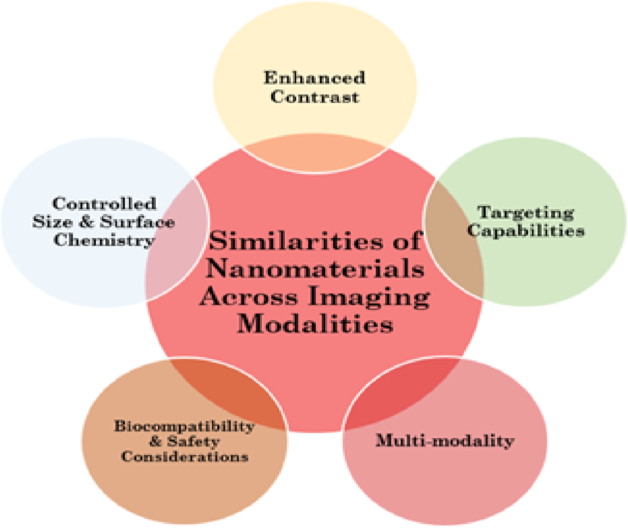

Figure 4: Similar action of nanoparticles used in different imaging modality

Lipid-Based: Nanocarriers: Lipid-based nanocarriers, like polymeric nanoparticles, are biodegradable and tunable for imaging and therapy [77].

Multimodal Imaging

Nanomaterials have revolutionized multimodal imaging by integrating multiple imaging techniques within a single platform, enhancing diagnostic accuracy and comprehensive disease assessment [78]. Various important nanomaterials include (figure 8),

Gold Nanoparticles (AuNPs): Used in CT, photoacoustic, and fluorescence imaging, AuNPs provide multifunctional imaging capabilities, improving tumor localization and diagnostic precision [79].

Magnetic-Plasmonic Nanoparticles: Combining magnetic nanoparticles with plasmonic nanomaterials enables MRI-photoacoustic hybrid imaging, allowing for deep-tissue visualization with enhanced contrast [80].

Table 4: Differences between various nanoparticles used in medical imaging

Feature	Magnetic Resonance Imaging	Computed Tomography	Ultrasound Imaging	Optical Imaging	PET/ SPECT Imaging
Main Role	Enhance magnetic properties (relaxivity)	Increase X-ray attenuation	Enhance acoustic reflection/ scattering	Fluorescent signal carriers	Carry radiotracers
Typical Nanomaterials	Superparamagnetic iron oxide (SPIONs), Gd-doped NPs	Gold NPs, Bismuth NPs, Hafnium oxide NPs	Gas-filled microbubbles, nanobubbles, phase-change NPs	Quantum dots, carbon dots, dye-doped silica NPs	Radiolabeled liposomes, silica NPs, dendrimers
Mechanism of Contrast	Proton relaxation via magnetic interactions	High atomic number elements attenuate X-rays	Acoustic impedance mismatch	Absorption/ emission of photons	Decay of radionuclides emitting γ/β+ particles
Resolution	Moderate (mm)	High (µm-mm)	Moderate (mm)	High (µm)	High (mm-cm)
Depth Penetration	High	High	Moderate	Low–Moderate	Very High
Use in Theranostics	Common (e.g., MRI-guided therapy)	Possible (e.g., gold for therapy + CT)	Less common but emerging (triggered drug release)	Very common (imaging + photodynamic therapy)	Very common (PET + drug delivery)

Table 5: Nanomaterial applications in various medical imaging modalities

ea of Application	Types of Nanomaterials involved	Imaging Modality	Purpose / Benefit
ncer Detection & agnosis	Quantum Dots, Iron Oxide Nanoparticles, AuNPs, Dendrimers	MRI, CT, Optical, PET, Photoacoustic	Targeted imaging, early detection, and improved tumour contrast
ain Imaging	Iron Oxide Nanoparticles, Dendrimers, Liposomes	MRI, PET	Penetration of Blood-brain barrier, and monitoring of neuronal activity
rdiovascular aging	AuNPs, Iron Oxide Nanoparticles, Polymeric Nanoparticles	CT, MRI, Ultrasound	Vascular inflammation, blood flow, and plaque imaging
mph Node Mapping	Quantum Dots, AuNPs, Silica Nanoparticles	Optical Imaging, CT, PET	Identification of sentinel lymph nodes, staging of cancer
ug Delivery + aging eranostics)	Liposomes, Polymeric Nanoparticles, AuNPs, Silica Nanoparticles	MRI, CT, Optical, PET	Drug distribution tracking in real time, with dual therapeutic and diagnostic applications
ne Imaging	Gold NPs, Silica Nanoparticles, UCNPs	CT, Optical	Bone disease diagnosis and high contrast of bone structure
ep Tissue Imaging	UCNPs, CNTs	NIR Optical, Photoacoustic	Improved penetration of tissue, reduced background signal
poxia & Oxygen apping	Perfluorocarbon Nanodroplets	MRI (19F), Ultrasound	Mapping the amount of oxygen in tissues, particularly tumours

Upconversion Nanoparticles (UCNPs): These nanoparticles enable fluorescence, MRI, and photoacoustic imaging, providing high-resolution, real-time imaging for biomedical applications [81].

Silica-Coated Nanoparticles: Used in PET-MRI and fluorescence-photoacoustic imaging, these nanoparticles facilitate highly sensitive multimodal imaging applications [82].

Polymeric Hybrid Nanoparticles: Engineered for combining MRI, optical, and ultrasound imaging, they enhance precision diagnostics and targeted imaging approaches [83].

A variety of imaging modalities are using nanomaterials more and more because of their special size-dependent characteristics, versatility, and capacity to be tailored for contrast enhancement and targeting. The following compares the similarities (figure 4) and contrasts (table 4) between the use of nanomaterials in various imaging modalities, such as ultrasound, MRI, CT, PET/SPECT, and optical imaging (fluorescence/bioluminescence).

Nanomaterials' improved sensitivity, multimodal capabilities, and tailored distribution have completely changed medical imaging. Because to their special physicochemical characteristics, which include their large surface area, adjustable size, and functionalization potential, biological processes at the molecular and cellular levels can be precisely visualized. By greatly enhancing picture contrast, these materials facilitate the early detection of illnesses like cancer, heart disease, and neurological disorders [84]. A comprehensive summary of the major applications of nanomaterials in medical imaging is shown in table 5.

Challenges and Limitations

Despite the significant advancements nanomaterials have brought to medical imaging, several challenges and limitations hinder their widespread clinical adoption.

Biocompatibility and Toxicity

The interaction of nanomaterials with biological systems raises concerns about potential toxicity, immune responses, and long-term biocompatibility. Some nanoparticles may accumulate in organs such as the liver and spleen, posing risks of toxicity and adverse side effects [85]. For example, Cadmium selenide (CdSe) quantum dots are known for their impressive fluorescence, making them ideal for optical imaging. However, they release toxic cadmium ions, which can accumulate in organs and cause cellular damage.

Stability and Degradation

Nanoparticles must maintain their structural integrity and functionality under physiological conditions. Issues such as aggregation, degradation, or unexpected interactions with biomolecules can impact their imaging performance and safety [86]. Feridex, an MRI agent incorporating SPIONs, was terminated due to stability problems and uneven performance because their aggregation or degradation impacted imaging quality and safety

Regulatory and Ethical Hurdles

The complex nature of nanomaterials makes regulatory approval challenging. Stringent testing and validation processes are required to ensure their safety and efficacy, often leading to long and expensive approval timelines. Ethical concerns regarding long-term effects and potential misuse also need to be addressed [87,88]. The FDA took a long time to approve PEGylated liposomes like Doxil® because they needed a lot of testing, but dendrimers need to be carefully examined for any long-term impacts before being approved.

Manufacturing and Scalability

Large-scale production of nanomaterials with consistent quality, reproducibility, and cost-effectiveness remains a challenge. Variations in synthesis methods can lead to batch-to-batch inconsistencies, affecting clinical reliability [89,90]. Although gold nanorods improve OCT and photoacoustic imaging, their commercialisation is hindered by batch-to-batch variability that affects uniformity and challenging aspect ratio control.

Clearance and Bio-distribution

Efficient clearance from the body is crucial to avoid long-term accumulation and toxicity. Many nanomaterials exhibit slow clearance rates, requiring careful design to enhance biodegradability and excretion through natural pathways [91]. Deep tissue imaging and therapy are made possible by CNTs, however their poor biodegradability and organ accumulation present toxicity issues. Non-functionalized forms of CNTs cause chronic inflammation and restrict clinical application.

Limited Clinical Translation

Despite promising preclinical results, very few nanomaterial-based imaging agents have successfully transitioned into routine clinical use. The gap between laboratory research and clinical application is often due to unresolved safety concerns, complex regulatory pathways, and high development costs [92]. Although gold-iron oxide hybrid nanoprobes have potential for MRI and optical imaging, safety, regulatory, and scalable production issues prevent them from being clinically translated.

Future Prospects

The future of nanomaterials in medical imaging is highly promising, with continuous advancements in biocompatibility, targeted imaging, and artificial intelligence-driven image analysis. Novel multifunctional nanoplatforms, smart contrast agents, and personalized imaging approaches will further enhance diagnostic capabilities [93]. As research continues to address current limitations, nanomaterial-based imaging will play a pivotal role in the next generation of medical diagnostics and theranostics. As research progresses, the following trends and developments are anticipated:

Integration with Artificial Intelligence (AI): AI-powered image analysis combined with nanomaterial-based imaging can improve diagnostic accuracy, automate disease detection, and facilitate real-time image interpretation. AI improves dynamic contrast enhanced (DCE) imaging by leveraging the kinetics of nanoparticle accumulation in pathological tissues (e.g., time-series from SPION-based MR imaging or QD-based fluorescence imaging) [94]. Polydopamine, silk fibroin, and PLGA-based nanocarriers generally degrade into non-toxic byproducts.

Development of Biodegradable and Biocompatible Nanomaterials: Advances in green nanotechnology will lead to the synthesis of safer, non-toxic, and biodegradable nanomaterials, addressing concerns regarding long-term accumulation and toxicity [95]. Carbon dots (CDs) and ultrasmall gold clusters (d”5 nm) have renal clearance. Enzyme-responsive linkers (e.g., cathepsin B-cleavable peptides) allow for smart and convenient degradation in tumor microenvironments.

Personalized and Targeted Imaging: Functionalized nanomaterials will enable precision medicine by allowing patient-specific imaging approaches, improving early disease detection and treatment monitoring [96]. Using aptamers, antibodies, folic acid, or peptides (RGD, iRGD) to target overexpressed receptors (for example, HER2, integrin ávâ3).

Hybrid and Multimodal Imaging Platforms: The development of smart nanomaterials capable of integrating multiple imaging techniques will enhance diagnostic precision, providing more comprehensive information about disease progression [97]. Trimodal nanoplatforms (PET/MRI/Optical) for comprehensive tumor staging and treatment planning.

Clinical Translation and Regulatory Approvals: Overcoming current regulatory challenges will accelerate the clinical adoption of nanomaterials, making them widely available for routine medical imaging applications [98]. Development of GMP-compliant protocols for synthesis of nanoprobes (e.g., PEGylated SPIONs, FDA-approved Ferumoxytol).

Advancements in Theranostics: The combination of diagnostic and therapeutic functionalities within a single nanomaterial system will lead to improved treatment monitoring and personalized medicine approaches [99].

Deep-Tissue Imaging and Non-Invasive Techniques: Innovations in nanotechnology will facilitate deeper tissue penetration with minimal invasiveness, improving imaging capabilities for complex diseases such as cancer and neurodegenerative disorders. Melanin-mimetic nanoparticles absorb NIR light and emit ultrasound for real-time vascular imaging [100].

While these advancements offer exciting opportunities, continued interdisciplinary collaboration between nanotechnology researchers, medical professionals, and regulatory agencies is essential for successfully translating nanomaterials into clinical practice. By addressing current limitations and leveraging emerging technologies, nanomaterials are poised to redefine the future of medical imaging, enabling earlier disease detection, higher accuracy, and improved patient outcomes.

Conclusion

Nanomaterials have emerged as powerful tools in medical imaging, offering enhanced contrast, improved sensitivity, and multifunctionality across modalities such as MRI, CT, fluorescence imaging, and photoacoustic imaging. Their unique physicochemical properties enable targeted imaging, facilitating early disease detection and precision diagnostics. Recent advancements in nanotechnology have led to the development of highly specific imaging agents, improving diagnostic accuracy and patient outcomes. Despite these breakthroughs, several challenges hinder their widespread clinical application. Issues related to biocompatibility, toxicity, long-term stability, and potential adverse effects must be addressed to ensure patient safety. Additionally, regulatory hurdles pose significant barriers to translating these innovations from research to clinical practice. Standardized protocols and rigorous testing are necessary to establish the safety and efficacy of nanomaterials in medical imaging. Looking ahead, integrating nanotechnology with artificial intelligence and personalized medicine holds immense promise. AI-driven analysis can enhance image interpretation, while patient-specific nanomaterials may enable more precise diagnostics and targeted therapies. Continued research and collaboration between scientists, clinicians, and regulatory agencies are crucial for overcoming current limitations and unlocking the full potential of nanomaterials in medical imaging. With these advancements, nanotechnology is poised to revolutionize diagnostic imaging, improving early detection, treatment planning, and overall healthcare outcomes.

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