Nanotechnology and Nanomaterials Research

Short Communication

DOI: https://doi.org/10.47275/2692-885X-129
Volume 6 Issue 1

Translational Nanotechnology in Clinical Medicine: A Review on Advances in Imaging Modalities and Surgical Interventions

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Abstract

The rapid advancement of nanotechnology has ushered in transformative innovations in clinical medicine, particularly in imaging modalities and surgical interventions, addressing critical gaps in diagnostic accuracy and therapeutic precision. This review highlights the urgent need to synthesize recent developments, as the integration of nanomaterials offers unparalleled opportunities to enhance disease detection, intraoperative navigation, and tissue regeneration while overcoming longstanding limitations in conventional techniques. By examining cutting-edge research and clinical applications, this paper underscores the potential of nanotechnology to bridge the gap between laboratory discoveries and patient-centered care. The discussion encompasses the role of nanoparticles in improving imaging resolution and specificity across modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and fluorescence imaging, as well as their utility in multimodal theranostic platforms. Insights are provided into how nanotechnology enables real-time tumor delineation, targeted drug delivery, and precision surgery, significantly reducing positive margins and improving patient outcomes. Additionally, the review explores nanomaterials' contributions to tissue repair, including regenerative scaffolds and smart wound dressings. Challenges such as biocompatibility, scalability, and regulatory hurdles are critically analyzed, alongside strategies to optimize nanoparticle design for clinical translation. Future prospects emphasize the integration of AI-driven nanotechnology, biodegradable nanosystems, and interdisciplinary collaboration to advance personalized medicine. The continued evolution of this field promises to revolutionize diagnostics, surgical precision, and therapeutic efficacy, ultimately reshaping the landscape of modern healthcare.

Keywords: Biocompatibility, Imaging modalities, Nanomaterials, Precision surgery, Regenerative medicine, Theranostics, Translational nanotechnology

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Citation: Sudunagunta A, Kumari SS, Banday HF (2025) Translational Nanotechnology in Clinical Medicine: A Review on Advances in Imaging Modalities and Surgical Interventions. Nanotechnol Nanomater Res, Volume 6:1. 129. DOI: https://doi.org/10.47275/2692-885X-129

Received: June 15, 2025; **Accepted:** August 08, 2025; **Published:** August 13, 2025

Introduction

The convergence of nanotechnology and clinical medicine is revolutionizing healthcare, offering innovative solutions for diagnosis, treatment, and monitoring of various diseases [1-3]. This review explores the advancements in translational nanotechnology, specifically focusing on its impact on imaging modalities and surgical interventions. By leveraging the unique properties of nanomaterials, researchers and clinicians are developing more precise, effective, and less invasive methods for managing complex medical conditions [4-6]. The goal is to bridge the gap between laboratory discoveries and clinical practice, ultimately enhancing patient outcomes.

In imaging, nanomaterials offer tailored solutions that significantly improve the resolution, contrast, and target efficiency of diagnostic techniques [7, 8]. Their unique physicochemical properties-such as high surface-area-to-volume ratios, tunable optical behavior, and magnetic responsiveness-enable more accurate visualization of pathologies, particularly in oncology and cardiovascular medicine [9-11]. Nanoparticle-based contrast agents are now being designed not only to enhance conventional modalities like MRI, CT, and positron emission tomography (PET) but also to facilitate emerging techniques such as photoacoustic and near-infrared (NIR) fluorescence imaging [12-14]. Moreover, the advent of multifunctional and theranostic nanoparticles has expanded the role of imaging from mere visualization to simultaneous diagnosis and treatment monitoring, representing a paradigm shift in clinical diagnostics [15-17].

In parallel, surgical practice is undergoing a transformation driven by nanotechnology's role in enhancing intraoperative precision and postoperative outcomes [18, 19]. Nanoparticles, engineered for image-guided surgery, enable real-time tumor delineation, thereby minimizing residual disease and preserving healthy tissue [20, 21]. Additionally, persistent luminescent and environment-responsive nanoparticles allow for deeper tissue visualization and sharper margin definition, especially in minimally invasive procedures [22]. These innovations contribute not only to improved resection accuracy but also to reduced complications, shorter recovery times, and better long-term prognosis for patients undergoing complex surgeries [23, 24].

Despite these promising developments, challenges remain in translating nanotechnological advances into routine clinical use. Issues such as biocompatibility, scalability, regulatory approval, and long-term safety continue to hinder widespread adoption [25, 26]. Nevertheless, ongoing interdisciplinary collaboration among materials scientists, clinicians, and regulatory bodies is accelerating the pace of innovation. As clinical trials advance and regulatory frameworks evolve, nanotechnology is poised to become an integral component of modern medicine, offering transformative solutions in both diagnostics and therapeutics [27, 28].

Nanotechnology in Imaging Modalities

Nanotechnology has emerged as a transformative force in the field of medical imaging, offering innovative solutions that enhance the accuracy and efficacy of diagnostic techniques [29, 30]. By leveraging the unique properties of nanomaterials, researchers are developing advanced imaging modalities that not only improve visualization but also facilitate targeted therapies (Table 1) [31, 32]. This section explores the integration of nanotechnology in various imaging modalities, highlighting its applications, benefits, and challenges.

Enhanced imaging with nanoparticles

The incorporation of nanotechnology into imaging modalities has significantly improved the early diagnosis and monitoring of diseases, particularly cancer (Figure 1) [33]. Traditional imaging techniques often fall short in sensitivity and specificity, especially in detecting small tumors or assessing treatment responses. Nanoparticles, due to their nanoscale size and tunable properties, can enhance the contrast and resolution of imaging modalities such as MRI, CT, and optical imaging [34-36]. Nanotechnology has significantly advanced medical imaging by enabling the development of contrast agents that offer improved resolution, sensitivity, and specificity. Nanoparticles can be engineered

Table 1: Unique properties of nanomaterials and their connection to advanced imaging modalities.

Unique property of nanomaterials	Relevance to imaging	Imaging modality type	Application/benefit
High surface-area-to-volume ratio	Allows dense functionalization with contrast agents or ligands	CT, MRI, PET, optical imaging	Improved sensitivity and targeting capability
Tunable optical properties	Enables control over emission wavelength and intensity	Fluorescence, NIR, photoacoustic	Enhanced tissue penetration and image clarity
Magnetic responsiveness	Enhances contrast in magnetic fields	MRI	Improved signal contrast, especially in soft tissues
Quantum effects on the nanoscale	Generates bright and stable fluorescence	Quantum dot imaging	Long-term tracking and high-resolution imaging
Biocompatibility and biodegradability	Ensures safety and clearance from the body	All *in vivo* modalities	Safe for repeated use in clinical and preclinical settings
Controlled size and shape	Influences biodistribution and tumor accumulation	PET, SPECT, optical imaging	Passive targeting via enhanced permeability and retention effect
Surface modifiability	Enables ligand attachment for active targeting	Targeted fluorescence/MRI	Selective imaging of diseased tissues or cancer cells
Photothermal and photodynamic capabilities	Convert light into heat or ROS for combining imaging and therapy	Photoacoustic, NIR, theranostics	Real-time imaging-guided therapy (e.g., tumor ablation or drug release)
High loading capacity	Can carry both imaging agents and drugs	Theranostics	Dual function: diagnosis and treatment within a single nanoplatform

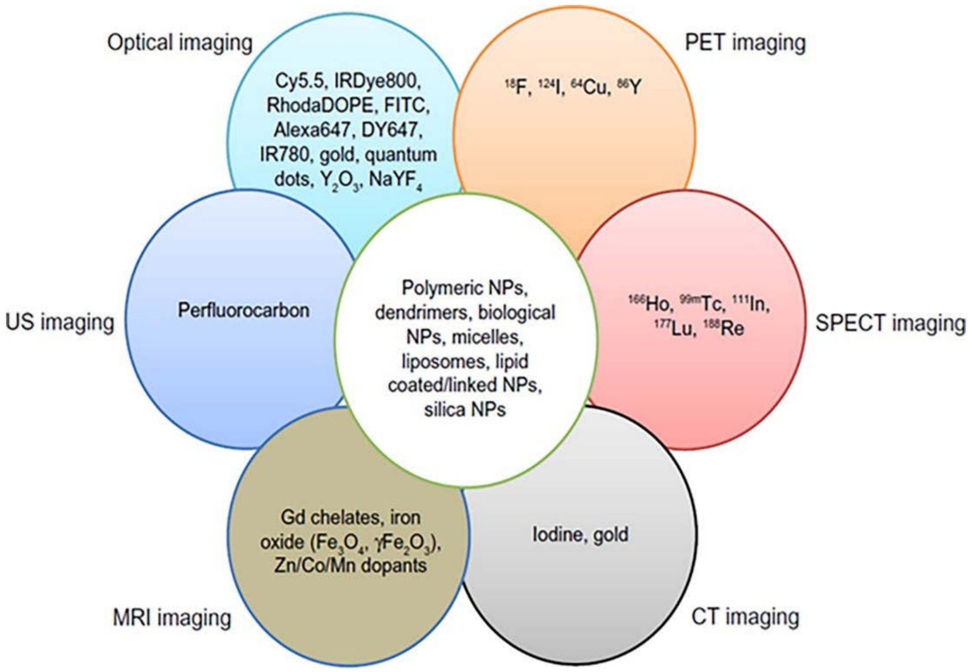

Figure 1: A variety of nanoparticles equipped with different labels can be used in various imaging modalities [33].

to target specific cells or tissues, allowing for more accurate detection and characterization of diseases such as cancer and atherosclerosis [37, 38]. For instance, in cancer imaging, nanoparticles can function as contrast agents to improve tumor margin visibility [1, 20], aiding in more precise surgical resections and reducing the occurrence of positive surgical margins, which negatively impact treatment outcomes [20].

Different imaging modalities benefit from nanotechnology-enhanced contrast. Optical imaging, ultrasound, CT, MRI, and nuclear medicine imaging are all being improved through the use of nanoparticles [20]. MRI, for example, can be enhanced using nanoparticles that improve the contrast between healthy and diseased tissue, enabling earlier and more accurate diagnoses [39]. Similarly, nanotechnology-based contrast agents are being developed to specifically target macrophages in atherosclerotic plaques, enabling the identification of advanced lesions and assessment of therapeutic efficacy [38]. For instance, the use of multifunctional nanoparticles in imaging allows for simultaneous diagnosis and therapy, a concept known as theranostics. These nanoparticles can be engineered to carry imaging agents and therapeutic drugs, enabling real-time monitoring of treatment efficacy while delivering targeted therapy [36, 40]. Recent studies have demonstrated the potential of nanoparticles in enhancing the sensitivity of optical imaging techniques, such as fluorescence and photoacoustic imaging, which are crucial for visualizing cancer biomarkers *in vivo* [40, 41].

Fluorescent nanoparticles in molecular imaging

Fluorescent nanoparticles, including quantum dots and dye-doped nanoparticles, have gained prominence in molecular imaging due to their high photostability and brightness [42-44]. These nanoparticles serve as effective probes for visualizing biological processes at the molecular level, allowing for the non-invasive determination of diseased tissues and monitoring of cellular dynamics [35, 45]. The ability to design nanoparticles with specific targeting ligands further enhances their utility in imaging, as they can selectively bind to cancer cells, improving diagnostic accuracy [37, 45]. Recent advancements have also highlighted the role of nanotechnology in developing imaging agents that can provide real-time feedback during surgical procedures. For example, nanoparticles can be utilized as contrast agents in image-guided surgery, helping surgeons accurately delineate tumor margins and reduce the risk of positive surgical margins [20, 46]. This integration of nanotechnology into surgical imaging represents a significant step forward in improving patient outcomes.

A study by Chung et al. [47] presents several significant findings regarding the use of targeted biodegradable NIR fluorescent silica nanoparticles (CEA-FSNs) for imaging colorectal cancer. The researchers successfully developed CEA-FSNs by tuning their size to between 50 to 200 nm and conjugating them with an antibody specific to carcinoembryonic antigen (CEA). This modification aimed to enhance the capability of the nanoparticles towards colorectal cancer cells. *In vitro* experiments demonstrated that CEA-FSNs bound more effectively to HT29 cells (which are CEA positive) compared to HCT116 cells (which are CEA negative). This indicates that the nanoparticles can selectively target cancerous cells expressing CEA. The study found that smaller CEA-FSNs were internalized into HT29 cells more efficiently than larger ones. This suggests that size plays a crucial role in the effectiveness of the nanoparticles for cellular uptake. After intravenous administration of CEA-FSNs in xenografted mice, a significantly greater fluorescent signal was observed in CEA-positive HT29 tumors compared to CEA-negative HCT116 tumors. This result highlights the potential of CEA-FSNs for distinguishing between cancerous and non-cancerous tissues *in vivo*. In F344-PIRC rats, the study successfully detected intestinal polyps using white-light endoscopy. Following the topical application of CEA-FSNs, NIR fluorescent signals were identified in the excised intestinal tissue, indicating the nanoparticles' effectiveness in highlighting cancerous lesions. The immunofluorescence imaging of excised tissue sections showed that the signals from CEA-FSNs co-registered with signals for both colorectal cancer and CEA. This further confirms the specificity and potential utility of CEA-FSNs as molecular imaging markers for early diagnosis of colorectal cancer. These results collectively suggest that CEA-FSNs hold promise as a novel tool for the early detection and imaging of colorectal cancer, potentially improving diagnostic accuracy and treatment outcomes [47].

Multimodal imaging approaches

The integration of nanotechnology with multiple imaging modalities is another area of advancement. Nanotechnology has emerged as a transformative force in the field of medical imaging, particularly in multimodal imaging approaches (Figure 2) [48]. By

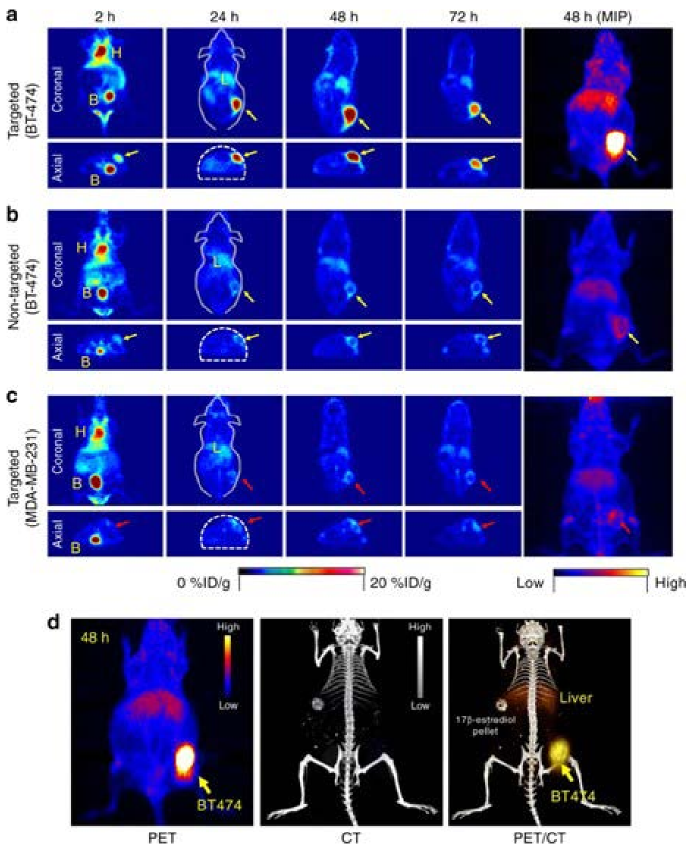

Figure 2: *In vivo* HER2-targeted PET imaging was conducted using xenograft breast cancer models. Serial coronal and axial PET scans were obtained at 2, 24, 48, and 72 h following intravenous injection of radiolabeled nanoparticle immunoconjugates in tumor-bearing mice (N = 5 per group). The study included: **(a)** a HER2-targeted group administered ^{89}Zr-DFO-scFv-PEG-Cy5-C' dots in BT-474 (HER2-positive) mice, **(b)** a non-targeted control group receiving ^{89}Zr-DFO-Ctr/scFv-PEG-Cy5-C' dots in BT-474 mice, and **(c)** a targeted group given ^{89}Zr-DFO-scFv-PEG-Cy5-C' dots in MDA-MB-231 (HER2-negative) mice. Maximum intensity projection (MIP) images were acquired at 48 h post-injection for all groups. Organs were labeled in the scans as H (heart), B (bladder), and L (liver). Panel **(d)** shows representative MIP PET, CT, and fused PET/CT images for a BT-474 mouse administered the targeted probe. Yellow arrows indicate BT-474 tumors, while red arrows mark MDA-MB-231 tumors [48].

integrating various imaging modalities, nanotechnology enhances the sensitivity, specificity, and overall effectiveness of diagnostic and therapeutic applications. Multicontrast spectroscopy and imaging techniques, such as Raman spectroscopy, are being translated into clinical applications by developing compact, automated instruments [49]. These multimodal approaches provide a more comprehensive view of the disease state, aiding in surgical guidance, intraoperative histopathological examination, and therapy monitoring [49]. The Radiological Society of North America promotes such innovations through its journals, including "Radiology: Artificial Intelligence" and "Radiology: Cardiothoracic Imaging" [50].

Nanotechnology plays a pivotal role in improving cancer imaging techniques. For instance, Cheng et al. [51] highlights the potential of optical nanoprobes to provide real-time imaging of tumor hypoxia, a critical factor in cancer progression. These nanoprobes not only enhance imaging capabilities but also allow for simultaneous drug delivery, thereby offering a dual approach to cancer treatment. Sheng et al. [52] further illustrates the application of perfluorocarbon nanodroplets in ultrasound and fluorescence imaging, which enable deep tumor penetration and controlled drug delivery. This multimodal imaging approach allows for real-time monitoring of drug release and therapeutic efficacy, addressing common challenges in cancer therapy. Moreover, the integration of MRI with nanotechnology has shown promise in predicting disease progression, as demonstrated by Zhou et al. [53]. Their work emphasizes the importance of multimodal MRI in understanding the structural and functional changes associated with Alzheimer's disease, showcasing the versatility of nanotechnology in various medical fields.

A study by Zhao et al. [54] presented several significant findings regarding the use of multifunctional nanoparticles as contrast agents for imaging pancreatic ductal adenocarcinoma (PDAC). The researchers created a core-shell structured gold nanorod (AuNR) designed for multimodal imaging. This nanoparticle consists of a AuNR core, a mesoporous silica layer, and a gadolinium oxide carbonate shell (AuNR-SiO_2-Gd). In Phantom studies, the AuNR-SiO_2-Gd nanoparticles demonstrated superior imaging capabilities, they provided higher contrast in MRI compared to Gadovist, and they exhibited greater X-ray attenuation than Visipaque, indicating better performance in X-ray CT. The nanoparticles produced a strong and stable signal in photoacoustic imaging, with a peak at 800 nm, which is beneficial for imaging applications. When tested in control mice, the AuNR-SiO_2-Gd nanoparticles showed significant contrast enhancement in the liver and spleen after intravenous administration. This suggests effective accumulation and imaging potential in these organs. The utility of these nanoparticles was further evaluated in a genetically engineered mouse model that mimics human PDAC, characterized by Kras and p53 mutations. The study found that, the nanoparticles accumulated in the surrounding soft tissues but were sparsely distributed within the tumor due to the dense stroma and poor vascularization typical of PDAC. This resulted in a negative contrast in CT and photoacoustic imaging within the tumor area, while MRI showed a positive contrast. The study concluded that AuNR-SiO_2-Gd nanoparticles have significant potential as a multimodal contrast agent for improving early diagnosis of PDAC, which could ultimately enhance clinical outcomes for patients suffering from this challenging cancer type. These results highlight the promising role of multifunctional nanoparticles in advancing imaging techniques for better detection and management of PDAC [54].

Another study by Song et al. [55] developed a new type of nanoparticle called magnetic particle imaging (MPI), MRI, Photoacoustic, Fluorescent (MMPF) nanoparticles, which combines iron oxide with semiconducting polymers. This design allows for multiple imaging techniques to be used simultaneously, which is beneficial for cancer detection in living mice. MMPF nanoparticles showed a long blood circulation time, with a half-life of approximately 49 h. This is significantly longer than many other iron oxide nanoparticles, which typically have a half-life of less than 5 h. The nanoparticles demonstrated high tumor uptake, reaching 18% of the injected dose per gram of tumor tissue. This is much higher than previously reported values for other iron oxide nanoparticles used in cancer imaging. In terms of imaging capabilities, MMPF nanoparticles provided excellent contrast in tumor imaging. For example, the MPI signal from tumors increased by 34.2 times after the injection of MMPF nanoparticles, indicating a strong ability to visualize tumors. The study also highlighted that MMPF nanoparticles could be used for imaging different types of tumors, including breast tumors and glioblastoma multiforme. In glioblastoma multiforme models, the MPI signal increased by 17.1 times after the injection, showcasing the effectiveness of these nanoparticles in detecting brain tumors. The nanoparticles were characterized by their stability and imaging performance. They maintained their imaging capabilities across various pH levels and hydrogen peroxide concentrations, which are typical in tumor environments. Overall, the results suggest that MMPF nanoparticles are a promising tool for multimodal cancer imaging, combining the strengths of different imaging techniques to improve tumor detection and monitoring [55].

Another study by Vojtech et al. [56] successfully synthesized three types of nanoparticles: Prussian blue (PB) nanoparticles, gadolinium-containing PB (GdPB), and manganese-containing PB (MnPB). The mean diameters of these nanoparticles were found to be 78.8 nm for PB nanoparticles, 164.2 nm for GdPB, and 122.4 nm for MnPB, indicating that they are monodisperse, which means they have a uniform size distribution. The synthesized nanoparticles exhibited moderate stability, with zeta potential measured at less than -30 mV, suggesting that they have sufficient surface charge to remain stable in solution. Cytotoxicity studies revealed that the nanoparticles were safe for use at certain concentrations. Specifically, PB nanoparticles showed negligible cytotoxicity at concentrations below 0.67×10^{-6} mg/cell, while GdPB and MnPB were safe at concentrations below 0.25×10^{-6} mg/cell. The nanoparticles were effective as MRI contrast agents. The study demonstrated that GdPB and MnPB could generate positive contrast in T1-weighted MRI sequences and negative contrast in T2-weighted sequences. This was evidenced by increased hyperintensities for GdPB and increased hypointensities for MnPB with rising concentrations. The biofunctionalized PB nanoparticles were able to fluorescently label targeted cells *in vitro*. For instance, GdPB nanoparticles modified with fluorescent avidin, and biotinylated antibodies successfully targeted specific cell populations, such as EoL-1 cells, while control nanoparticles without the targeting antibodies showed negligible binding. Flow cytometry confirmed the effectiveness of the biofunctionalized nanoparticles in labeling targeted cells, showing increased fluorescence in cells treated with the specific targeting nanoparticles compared to controls. Overall, the results indicate that the biofunctionalized PB nanoparticles are promising agents for multimodal molecular imaging, combining both fluorescence imaging and MRI capabilities [56].

While multimodal imaging using nanoparticles offers numerous advantages, it is important to consider the challenges and limitations associated with these technologies. The development of nanoparticles that are biocompatible, non-toxic, and capable of efficient targeting remains a critical area of research [57, 58]. Additionally, the translation of these technologies from preclinical studies to clinical applications requires rigorous validation and regulatory approval. Despite these challenges, the potential of nanoparticle-based multimodal imaging to revolutionize diagnostics and treatment in various medical fields is immense, and ongoing research continues to push the boundaries of what is possible in this exciting area of nanomedicine [59, 60].

Nanotechnology in Surgical Interventions

Nanotechnology has emerged as a transformative force in the field of medicine, particularly in surgical interventions (Table 2). By manipulating materials at the nanoscale, researchers and clinicians are developing innovative solutions that enhance surgical precision, improve patient outcomes, and reduce complications [61, 62]. Nanotechnology is being integrated into various surgical fields, including oncology, orthopedics, and ophthalmology. Its applications range from drug delivery systems to imaging techniques that enhance surgical precision. This section explores the various applications of nanotechnology in surgical interventions, highlighting its potential benefits and challenges.

Precision surgery and navigation

Nanotechnology plays a crucial role in enhancing surgical precision and navigation. Endoscopic navigation systems, a research hot spot in medical science, are benefiting from advanced endoscopic vision technologies [63]. These technologies utilize multiple endoscopic optical imaging modalities, including white-light endoscopy and contrast-enhanced imaging, to provide surgeons with detailed views of the surgical field [63]. Endoscopic vision, a specific application of computer vision, involves instrument tracking, endoscopic view expansion, and suspicious lesion tracking [63].

Image-guided surgery is another area where nanotechnology is making a significant impact. By using nanoparticles as contrast agents, surgeons can visualize tumors more clearly during surgery, improving resection accuracy [20]. This is particularly important in minimally invasive procedures, where the absence of tactile feedback necessitates reliance on imaging for guidance. This capability is vital for reducing positive surgical margins, which are associated with poor treatment outcomes [20, 64]. The integration of 3D printing, computational modeling, and artificial intelligence is further enhancing surgical planning and execution, especially in complex procedures such as transcatheter structural heart interventions [64]. pH sensitive another major approach which can be used to in precision surgery and navigation (Figure 3) [65].

Table 2: Outlining nanotechnology in surgical interventions.

Aspect	Details
Field of application	Surgical interventions
Role of nanotechnology	Enhancing surgical precision, intraoperative imaging, targeted therapeutic delivery
Key nanomaterials used	Gold nanoparticles, quantum dots, liposomes, polymeric nanoparticles, persistent luminescent nanoparticles
Nanocarrier function	Tumor targeting, drug/gene delivery, contrast enhancement, photothermal effect
Targeted site	Tumor margins, sentinel lymph nodes, inflamed or abnormal tissues
Main mechanisms	Image-guided surgery, real-time tracking, photothermal therapy, localized drug activation
Imaging modalities supported	NIR fluorescence, MRI, CT, photoacoustic imaging, optical imaging
Therapeutic integration	Photothermal ablation, chemotherapy, photodynamic therapy, theranostics
Benefits	Accurate resection, minimized collateral tissue damage, improved recovery, lower recurrence
Clinical stage/application	Preclinical trials, early-phase human trials, experimental surgical guidance tools
Challenges/considerations	Biocompatibility, long-term toxicity, regulatory approval, cost-effectiveness
Future prospects	Personalized nanomedicine, smart responsive systems, AI-integrated surgical platforms

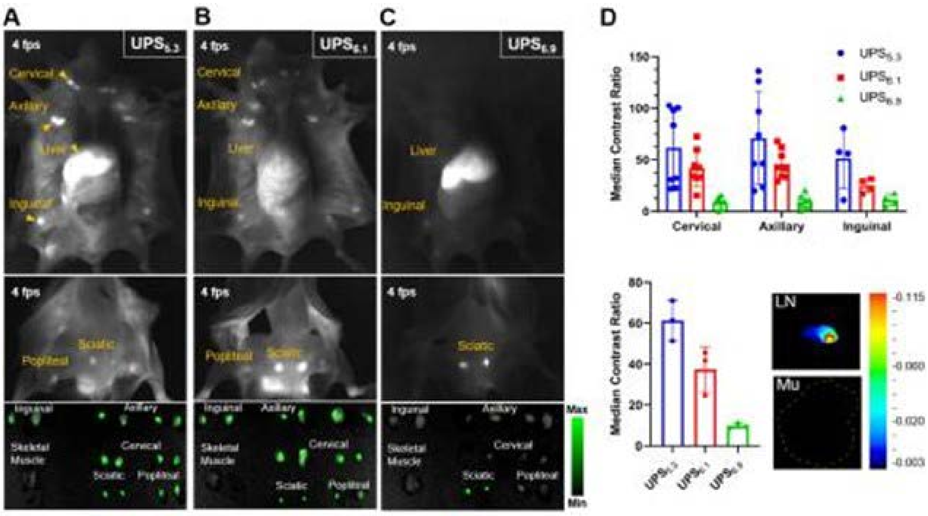

Figure 3: Whole-body NIR fluorescence imaging was performed on dissected, tumor-free BALB/cj mice to facilitate real-time, image-guided lymph node resection. **(A)** The use of $UPS_{5.3}$-ICG and **(B)** $UPS_{6.1}$-ICG effectively highlighted all superficial lymph nodes, enabling precise surgical removal under fluorescence guidance. **(C)** In contrast, $UPS_{6.9}$-ICG exhibited predominant liver accumulation, preventing its use for lymph node-guided resection. **(D)** Fluorescence intensity in lymph nodes was quantified and normalized against skeletal muscle, revealing that the contrast ratio for each anatomical lymph node group was influenced by the pKa of the polymeric micelle. Among the tested formulations, $UPS_{5.3}$ demonstrated the highest fluorescence signal across all lymph node anatomical regions [65].

A study by Yan et al. [66] on persistent luminescence nanoparticles aimed to enhance surgical navigation and precision resection in colorectal cancer. The nanoparticles demonstrated a high intensity of luminescence, which significantly improved the visibility of tumor tissues during surgery. This is crucial for surgeons to accurately identify and differentiate between malignant and healthy tissues. NIR persistent luminescent nanoparticles offer a promising approach for deep-tissue tumor imaging by emitting long-lasting luminescence even after excitation stops, thereby avoiding interference from tissue autofluorescence. In this study, we synthesized Cr^{3+}-doped zinc gallogermanate (ZGC) nanoparticles with a hydrodynamic size of 140 nm using a removable template technique and functionalized them with folic acid to produce ZGC-FA. These nanoparticles emitted NIR luminescence at 695 nm with an impressive *in vivo* signal-to-noise ratio of 23.9. Utilizing a luciferase-expressing colon cancer model, we demonstrated the effectiveness of ZGC-FA in precisely guiding tumor resection. Following intraperitoneal injection, the persistent luminescence accurately outlined tumor margins with a 98% overlap, enabling complete tumor removal with minimal damage to surround tissue (only 2.3% excised), highlighting ZGC-FA's potential in improving surgical precision and patient recovery in oncological procedures [66].

Another study by Li et al. [67] presents several significant results regarding the use of pH-activated NIR-II fluorescence imaging for precise tumor resection. The development of a hollow-structured calcium carbonate and polydopamine co-packed shell on Nd-doped downshifting nanocrystals significantly improved the targeting capacity of the NIR-II contrast nanoagent. This modification allows for better specificity in identifying tumor tissues compared to normal tissues. The NIR-II fluorescence of the nanoagent remains in an "OFF" state until it encounters the weakly acidic environment typical of tumor microenvironments. This pH-responsive behavior leads to the degradation of the hybrid nanoshell, effectively turning the fluorescence "ON" and enhancing imaging capabilities. The study demonstrated that the new nanoagent significantly augments the signal to background ratio, which is crucial for accurately delineating tumor borders from surrounding normal tissue. This improvement is essential for ensuring that surgeons can effectively identify and remove tumors. The application of this novel imaging technique allowed for thorough tumor removal during surgeries. Post-surgery evaluations indicated no significant *in situ* recurrence or metastases after 28 days, suggesting that the method not only aids in precise resection but also contributes to better surgical outcomes. The findings indicate a promising preclinical potential for using tumor microenvironment-activated nanoprobes in assisting with the accurate delineation of tumor margins, which could lead to advancements in surgical oncology. These results highlight the effectiveness of the developed NIR-II fluorescence imaging technique in improving tumor resection accuracy and outcomes, showcasing its potential for future clinical applications [67].

While the potential of nanoparticles in precision surgery is immense, there are challenges that need to be addressed. These include technological hurdles, regulatory considerations, and safety concerns associated with the clinical application of nanotechnology. Moreover, the transition from passive to active targeting in nanoparticle design is crucial for improving the specificity and efficacy of treatments. As research progresses, the integration of nanoparticles in surgical procedures is expected to revolutionize precision medicine, offering more effective and personalized treatment options for patients [68, 69].

Nanomaterials for tissue repair and regeneration

In addition to enhancing imaging and surgical precision, nanotechnology is also being used to promote tissue repair and regeneration. Nanomaterials can provide scaffolding structures or release growth factors to stimulate the growth of new blood vessels and support tissue repair after events like myocardial infarction [70]. These regenerative approaches hold significant implications for restoring cardiac function and minimizing long-term complications [70]. Furthermore, nanostructured scaffolds have advanced regenerative medicine by supporting stem cell differentiation, modulating cellular microenvironments, and enhancing tissue repair [71].

A study by Kim et al. [72] emphasizes the development of chitosan-based nanocomposites incorporating various materials such as silver, copper, gold, zinc oxide, titanium oxide, carbon nanotubes, graphene oxide, and biosilica. This combination aims to enhance the properties necessary for effective bone graft substitutes. The research highlights that these composite materials exhibit osteoconductive, osteoinductive, and osteogenic properties, which are crucial for successful bone repair. The materials promote the expression of important bone formation genes, including alkaline phosphatase, bone morphogenic protein, runt-related transcription factor-2, bone sialoprotein, and osteocalcin. *In vitro* studies demonstrated that the chitosan-based composites possess significant antibacterial activity. This is particularly important in preventing infections that can complicate bone healing. The mechanical properties of the composites were evaluated, showing that they have adequate stiffness and mechanical strength, which are essential for supporting bone structure during the healing process. The study also reports favorable tissue integration characteristics, indicating that the materials can effectively bond with surrounding tissues, which is vital for successful bone regeneration. The degradation behavior of the composite materials was assessed, revealing that they degrade at a suitable rate, allowing for gradual replacement by natural bone tissue as healing progresses. Overall, the findings suggest that biomimetic chitosan with biocomposite nanomaterials holds great promise for enhancing bone tissue repair and regeneration, addressing the limitations of traditional grafting methods [72].

The integration of nanotechnology into wound management has shown promising results. Nanomaterials can enhance the properties of wound dressings, promote faster healing and reduce infection rates. For instance, the use of nano-enzymes and smart materials in dressings has been shown to facilitate tissue regeneration and improve patient outcomes [73]. This advancement is particularly important in managing chronic wounds, which pose significant challenges in clinical settings. While nanomaterials offer significant advantages in tissue repair and regeneration, there are challenges and limitations that need to be addressed. The potential for nanomaterials to induce inflammation, particularly through the generation of reactive oxygen species, necessitates careful consideration of their biocompatibility and long-term effects in living systems [74].

Challenges and Future Directions

Despite the promising advancements in nanotechnology for imaging, several challenges remain. The biocompatibility and long-term stability of nanoparticles *in vivo* are critical factors that need to be addressed to ensure their safe application in clinical settings [37, 75]. Additionally, the regulatory landscape for nanomedicine is still evolving, which may impact the translation of these technologies from bench to bedside. Future research should focus on optimizing the design of nanoparticles to enhance their imaging capabilities while minimizing potential toxicity. The development of modular nanosystems that can accommodate multiple imaging modalities may also pave the way for more comprehensive diagnostic tools [30, 76]. As the field of nanotechnology continues to advance, it holds the potential to revolutionize medical imaging, leading to earlier detection and more effective treatment strategies for various diseases.

Overcoming translation barriers

Despite the promising advancements in nanotechnology, several challenges remain in translating these technologies into clinical practice. These challenges include nanoparticle-induced cytotoxicity, immunogenicity, scalability issues, and regulatory hurdles [71]. Afonin et al. [77] highlights the importance of addressing these barriers to advance nucleic acid nanoparticle technologies to the clinic. A recent workshop sponsored by the Kavli Foundation and the Materials Research Society discussed the future directions and current challenges for the development of therapeutic nucleic acid nanotechnology, emphasizing the need to overcome these barriers to realize the clinical grand challenge of TNA nanotechnology [77].

Regulatory and scalability issues

Regulatory challenges and scalability issues are significant obstacles in the translation of nanoengineered interventions into enhanced cancer therapies and patient management [1]. The need for extensive evaluation of long-term biocompatibility and pharmacokinetics of nanomaterials is critical [71]. Addressing these limitations requires collaboration across nanoscience, bioengineering, and translational medicine to refine nanoparticle functionalization, optimize safety profiles, and ensure equitable access to nanotherapeutics [71].

The importance of interdisciplinary collaboration

The successful translation of nanotechnology into clinical medicine requires interdisciplinary collaboration among researchers, clinicians, engineers, and regulatory agencies [1, 71]. By working together, these stakeholders can address the challenges and ensure that nanotechnology-based solutions are safe, effective, and accessible to patients. Furthermore, integrating precision medicine with a person-centered approach, as highlighted by Bierman et al. [78], can improve the quality and outcomes of care by accounting for individual patient factors such as multimorbidity and personal preferences.

Translational nanotechnology holds immense potential for transforming clinical medicine, particularly in the areas of imaging modalities and surgical interventions. By enhancing imaging resolution and specificity, enabling precision surgery, and promoting tissue repair and regeneration, nanotechnology is paving the way for more effective and less invasive treatments [20, 37, 70]. Overcoming the existing challenges and fostering interdisciplinary collaboration will be crucial in realizing the full potential of nanotechnology and improving patient outcomes in the years to come [71, 77]. The integration of AI-assisted nanotechnology and CRISPR-Cas9-mediated gene editing are driving next-generation precision medicine, integrating nanoscale therapeutics with computational approaches to enhance efficacy [71].

Conclusion

Nanotechnology is poised to play a pivotal role in the future of medical imaging, offering innovative solutions that enhance diagnostic accuracy and therapeutic efficacy. By integrating nanomaterials into imaging modalities, researchers are developing advanced tools that can significantly improve patient care. Also, nanotechnology has revolutionized multimodal imaging approaches, offering enhanced diagnostic and therapeutic capabilities in various medical fields, particularly oncology. The integration of nanotechnology with imaging modalities such as MRI, ultrasound, and fluorescence imaging has paved the way for innovative solutions in cancer detection and treatment. As research continues to advance, addressing the challenges of safety, instrumentation, and data analysis will be essential for the successful clinical translation of these technologies. The future of nanotechnology in multimodal imaging holds great promise for personalized medicine and improved patient outcomes.

Furthermore, nanotechnology holds significant potential to revolutionize surgical interventions by improving precision, enhancing therapeutic efficacy, and facilitating better patient outcomes. Continued research and collaboration among stakeholders will be vital in realizing the full benefits of this innovative technology in the surgical field. The future of nanotechnology in surgical interventions is promising, with ongoing research aimed at overcoming current challenges. Innovations in nanomaterials, such as biodegradable nanoparticles and multifunctional systems, are expected to enhance the efficacy of surgical treatments further. As the field continues to evolve, it is essential to maintain a focus on patient-centered outcomes and safety.

Acknowledgements

None.

Conflict of Interest

None.

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