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# THERANOSTICS: INTEGRATING DIAGNOSTIC IMAGING AGENTS AND THERAPEUTIC DRUGS INTO A SINGLE MULTIFUNCTIONAL NANO-PLATFORM FOR REAL-TIME MONITORING OF TREATMENT

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***ABSTRACT*:**

The field of Theranostics which combines treatment methods with diagnostic imaging through a compact nanoscale technology platform has emerged as one of the most significant advancements in current precision medicine practices. Through their ability to deliver therapeutic and imaging contrast materials via a single designed nanocarrier system theranostic platforms permit doctors to monitor drug distribution throughout the body while tracking tumor treatment results in real time which resolves the timing and location problems found in standard diagnostic procedures that follow the treatment path. The paper presents an extensive analysis of multifunctional theranostic nanosystem design principles and nanoplatform structures and imaging techniques and responsive drug delivery systems and their potential for clinical application. The study investigates fundamental classes of nanoplatforms which include superparamagnetic iron oxide nanoparticles (SPIONs) and liposomes and polymeric nanoparticles and gold nanostructures and quantum dots and hybrid systems together with their applications in various imaging techniques such as MRI and PET and CT and fluorescence and photoacoustic and ultrasound imaging. The paper discusses emerging problems which affect biocompatibility and regulatory approval and manufacturing scalability and clinical integration. The paper presents its argument that theranostic technology development will progress through AI-powered closed loop nanoplatforms which use real time imaging data to adjust treatment methods thereby creating a new form of customized medical care which uses visual diagnostics.

***Keywords**: Theranostics, Nanoplatform, Drug Delivery, Real-Time Monitoring, Mri, Pet Imaging, Spion, Liposome, Tumor Microenvironment, Multimodal Imaging, Precision Oncology, Stimuli-Responsive Release*

## INTRODUCTION

The medical profession currently experiences a deep-rooted problem because doctors use separate methods for patient diagnosis and treatment even though both imaging technology and drug treatment methods have achieved impressive growth. A patient through imaging acquires information about tumor location and characteristics while receiving a separate treatment plan which leads to follow-up imaging after several weeks to check their progress before treatment modifications occur. The sequential approach causes time waste which results in poor clinical outcomes because it cannot track how diseases and treatment reactions evolve for each patient in real-time.

Theranostics represents a new research area which combines the fields of therapeutics and diagnostics into a new approach that uses one developed nanoscale system to deliver both diagnostic imaging materials and therapeutic drugs to specific locations in the body. The term was first coined in the early 2000s and has since grown into one of the most actively investigated areas in nanomedicine with applications spanning oncology cardiology neurology infectious disease and autoimmune conditions.

The reasons for using nanoscale diagnostic and therapeutic systems together present a strong argument for their implementation. Tumor tissues preferentially absorb nanoparticles from the 1–200 nm size range because these particles use the enhanced permeability and retention effect which depends on the leaky blood vessels and defective lymphatic drainage systems that exist in solid tumors. The design of nanoparticles which transport imaging agents and therapeutic drugs together enables both elements to gather at the targeted area which results in an exact representation of drug distribution through imaging instead of using the image as an anatomical


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substitute. The nanoscale carriers provide control over drug release through controlled mechanisms and respond to external stimuli while enabling researchers to create surface features that achieve direct targeting and establish various imaging techniques which remain beyond the reach of standard small-molecule drugs and imaging agents.

## CONCEPTUAL FRAMEWORK AND DESIGN PRINCIPLES

### 2.1 Core Components of a Theranostic Nanoplatform

A complete theranostic nanoplatform needs four key elements which work together for its complete operation. The nanocarrier scaffold provides the structural foundation — a nanoscale vehicle (liposome, polymeric matrix, inorganic nanoparticle, or hybrid structure) with appropriate size, surface charge, stability, and biocompatibility to navigate biological barriers and reach the target tissue. The size of the material ranges from 10 to 200 nanometers which enables tumors to accumulate through EPR while protecting against excessive renal clearance. The imaging agent gives diagnostic power through a contrast agent which produces detectable signals in multiple clinical and preclinical imaging methods. Imaging agents include superparamagnetic iron oxide for MRI, and radiolabelled tracers (18F, 64Cu, 68Ga) for PET, and iodinated or gold-based materials for CT contrast, and fluorescent dyes or quantum dots for optical imaging, and photoacoustic-active chromophores.

The therapeutic payload provides the treatment function through its delivery of a chemotherapeutic drug and a photosensitizer and a photothermal agent and a gene therapy construct and an immunotherapeutic agent. The surface functionalization layer controls targeting selectivity and pharmacokinetics through three elements which include polyethylene glycol (PEG) coating that enables immune evasion and extended circulation and tumor-specific ligands which include antibodies and aptamers and peptides and small molecules and stimuli-responsive polymers which release drugs when they detect specific microenvironmental signals.

### 2.2 The Concept of Real-Time Treatment Monitoring

The primary benefit which theranostic platforms provide compared to traditional drug delivery systems allows their users to monitor treatment progress throughout the entire process. The nanocarrier system which delivers both imaging agent and therapeutic drug operates through its imaging signal to show how drugs distribute within the body and how they build up in tumors and through its design which responds to stimuli to show when drugs are released. Imaging signal intensity shows a strong relationship with therapeutic response in chemodynamic therapy systems because their fluorescence and photoacoustic signals achieved Pearson correlation coefficients of $r = 0.98$ and $r = 0.90$ which enabled researchers to observe therapeutic activity through dynamic visualization during real-time experiments.

The "companion diagnostics" paradigm changes imaging from an anatomical assessment tool into a therapeutic system which uses feedback to control its functions while it helps doctors to decide about dose increase and treatment continuation and regimen changes based on precise imaging results which they can access immediately instead of waiting for clinical assessment.

## NANOPLATFORM ARCHITECTURES

### 3.1 Liposomal Theranostic Systems

The most advanced theranostic nanocarriers used in medical practice today are liposomes. The dual structural design of the system which includes a hydrophilic core and a lipophilic shell permits the system to simultaneously store hydrophilic imaging agents and water-soluble drugs inside the core while it stores hydrophobic imaging probes and lipophilic drugs inside the bilayer. Researchers have created theranostic liposomes which use SPIONs and quantum dots to deliver therapeutic compounds for glioma surgery and imaging purposes. The QSC-Lip system which combines SPIONs and quantum dots with the therapeutic peptide cilengitide showed an encapsulation efficiency of ~88.9% for the drug component. The system has a particle diameter of $100 \pm 1.24$ nm and it shows biphasic drug release which includes an initial quick release that occurs within 10 hours followed by consistent drug release The system provides both precise MRI and fluorescence-guided tumor targeting. Liposomes that contain iron oxide nanoparticles and fluorescent agents which have been modified with tumor-homing peptides function as effective bifunctional agents for MRI and fluorescence imaging in theranostic applications that show promising results for atherosclerosis and cancer treatment.


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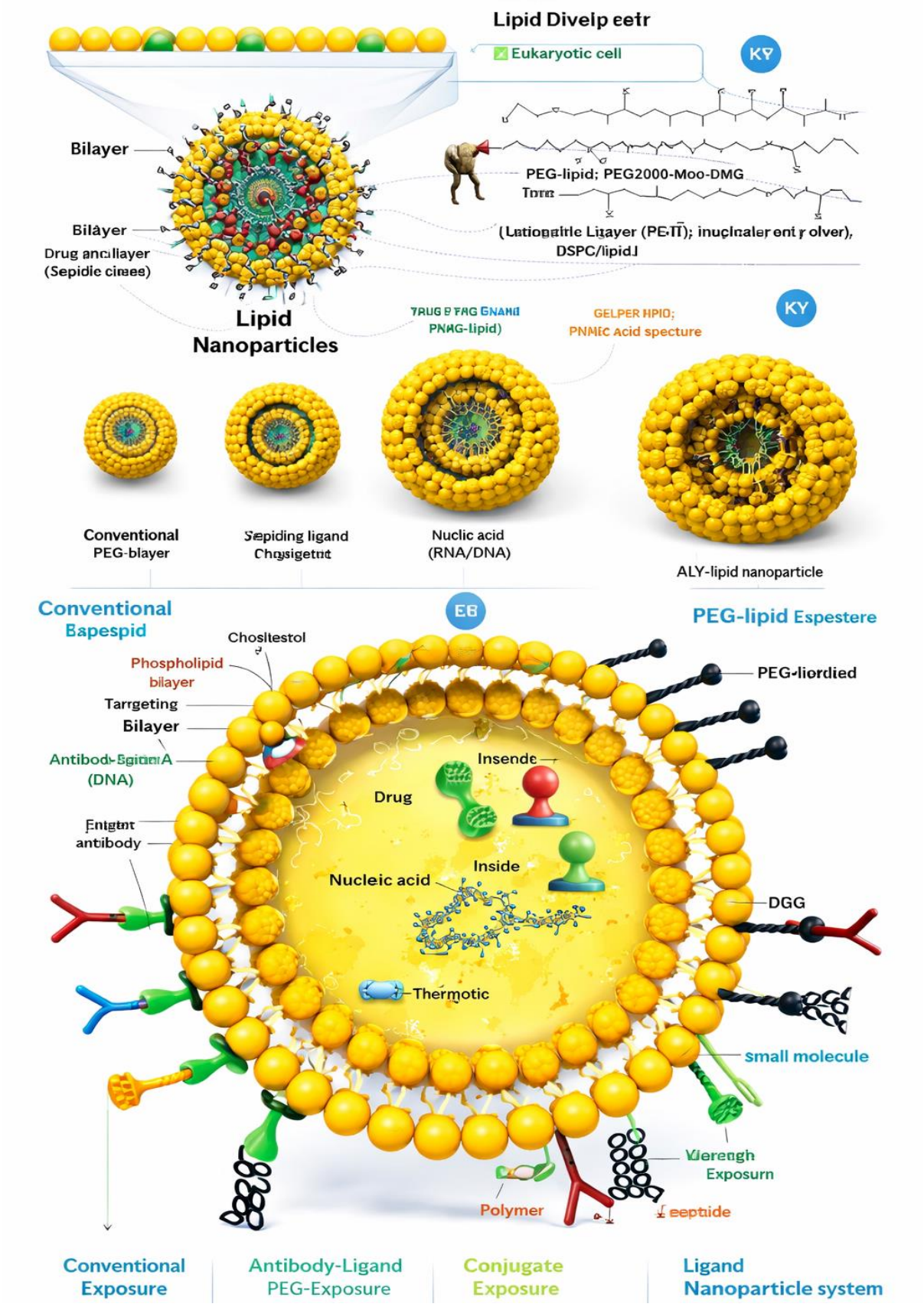


**Figure 1.1-Structural Composition and Functional Variants of Lipid Nanoparticles**


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### 3.2 Superparamagnetic Iron Oxide Nanoparticles (SPIONs)

The superparamagnetic properties of SPIONs make them the most researched nanomaterials which scientists use to develop theranostic systems because these materials create T2 MRI contrast while providing drug delivery systems and surface customization options. The treatment system uses pH-sensitive linkers to attach chemotherapeutic drugs on SPION surfaces which release drugs specifically to tumors when the acidic conditions of the tumor microenvironment activate the system. The SPION-based system contains rapamycin and uses the fluorescent dye Cy5.5 to create dual imaging capabilities while the PFN1 antibody targets blood vessels to deliver therapeutic effects which treat atherosclerotic lesions in preclinical studies. Scientists created ultra-small SPIONs which have a diameter of approximately 3 nanometers through high-temperature thermal decomposition and they developed dual-modality MRI and fluorescence probes through surface modifications which displayed vascular constriction in atherosclerotic models during Flash-3D MRI sequence imaging to show that SPIONs can treat both cardiovascular and cancer conditions.

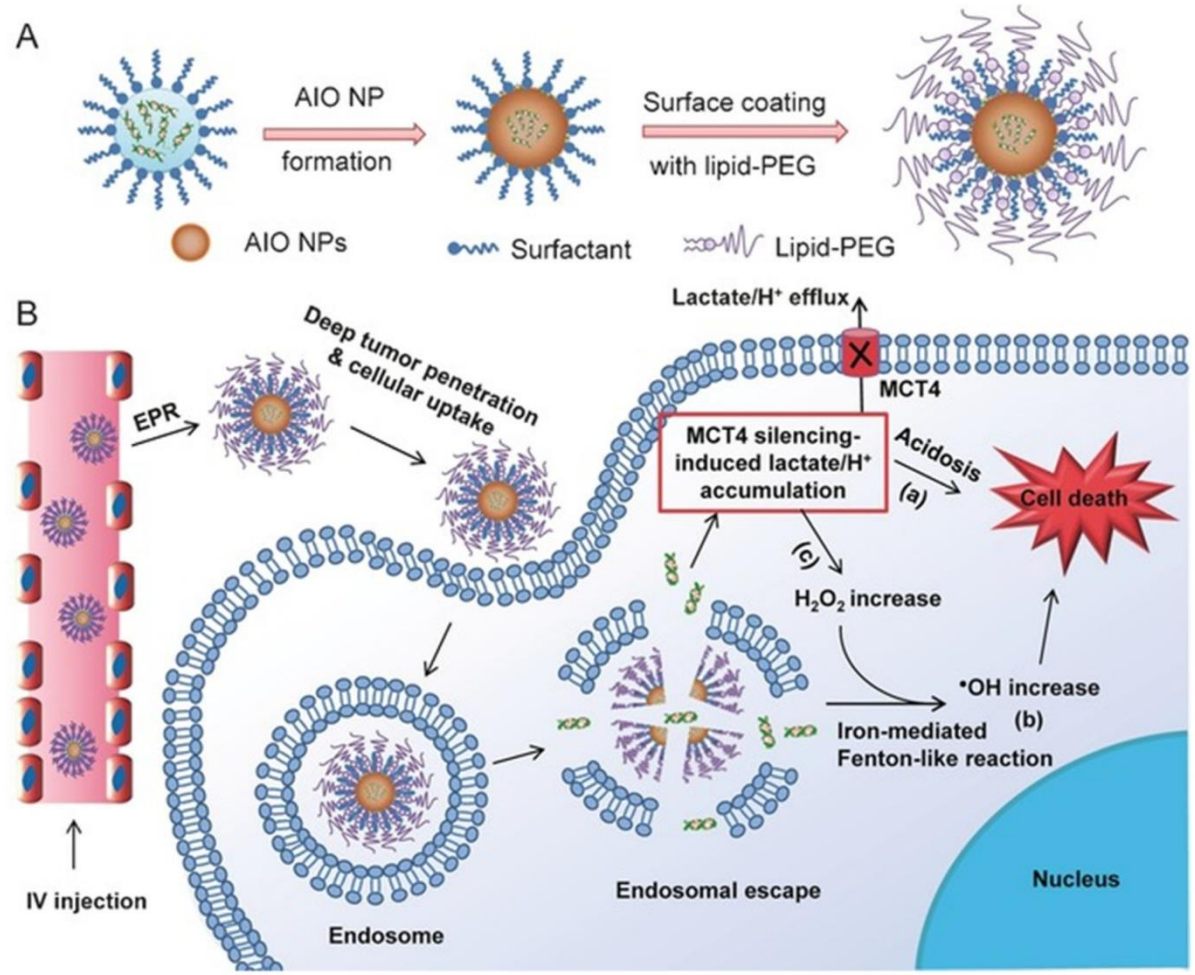


**Figure 1.2-Formation and Mechanism of Action of AIO Nanoparticles for Cancer Therapy**

### 3.3 Gold Nanostructures

Gold nanoparticles (GNPs) — including nanospheres, nanorods, nanocages, and nanoshells — function as versatile theranostic materials because their localized surface plasmon resonance (LSPR) properties and their chemical inertness and their adaptable surface chemistry enable various applications. The interaction of incident light with the coherent oscillation of conduction electrons at GNP surfaces generates intense light absorption and scattering which supports multiple imaging modalities: photoacoustic imaging (PAI), surface-enhanced Raman scattering (SERS), CT contrast enhancement, and two-photon fluorescence. GNP geometry determines the plasmon resonance wavelength because nanorods demonstrate near-infrared absorption which aspect ratio controls, which makes them suitable for deep-tissue photoacoustic imaging and photothermal therapy applications.


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The theranostic framework uses GNPs to connect four treatment methods which include PTT and PDT and chemotherapy and immunotherapy, while the treatment efficiency increases and the overall body effects decrease because the energy conversion occurs only at the tumor area. Plasmonic nanoplatforms create intelligent designs which respond to tumor microenvironments, while they enable real-time monitoring and adaptive treatment within closed-loop theranostic frameworks.

### 3.4 Polymeric Nanoparticles

The polymeric nanoparticles that researchers developed using biodegradable polymers such as PLGA and PLA and chitosan and HPMA-based copolymers enable researchers to precisely control their particle dimensions and surface characteristics and their ability to carry drugs and their response to external stimuli. Their biocompatibility and biodegradability make them attractive for clinical translation. The polymeric particles which researchers developed use manganese (Mn) and gadolinium (Gd) as paramagnetic metals to function as MRI T1 contrast agents while delivering chemotherapeutic drugs. The chitosan-based nanoplatforms that use doxorubicin and SPIONs show pH-dependent drug release and MRI contrast capabilities which enable effective theranostic use in glioma cell lines that exhibit excellent biocompatibility. The HPMA-based copolymers which researchers produced through Gd and therapeutic drug conjugation create a validated polymeric theranostic architecture which achieves 120-fold more cellular gadolinium uptake than Gd-DOTA which doctors currently use. The system produces substantial T1 MRI contrast enhancement and enables precise drug delivery.

### 3.5 Quantum Dots

Quantum dots (QDs) serve as advanced optical imaging agents in theranostic medicine because they are semiconductor nanocrystals which produce fluorescence that varies with their size while being excited by a wide range of light and emitting it through narrow symmetrical emission patterns. The material demonstrates superior performance for multiplexed in vivo fluorescence imaging because it maintains photostability and its quantum yield exceeds that of standard organic fluorophores while users can control its emission wavelength by changing the particle dimensions. The research used QDs which researchers integrated into yolk/shell-structured silica nanosystems that contained doxorubicin to achieve dual-modality PET/optical imaging in theranostic cancer models which showed that QD fluorescence together with drug distribution matched PET biodistribution data to confirm that co-delivered imaging and therapeutic agents show each other's distribution in a reliable way.

### 3.6 Hybrid and Biomimetic Systems

The most advanced theranostic architectures are hybrid nanoplatforms which combine multiple functional nanomaterials to create multiple imaging methods and different therapeutic mechanisms. The combined use of carbon-based nanomaterials (which include carbon nanotubes and graphene oxide and carbon dots) with metallic and metal oxide components enables the simultaneous use of multiple imaging methods which include fluorescence and photoacoustic and MRI and CT together with PTT and PDT and chemodynamic therapy (CDT) and ferroptosis induction. Biomimetic designs — including cell membrane-coated nanoparticles and exosome-based carriers — exploit natural cell surface proteins to achieve immune evasion, homotypic tumor targeting, and long systemic circulation times.

## IMAGING MODALITY INTEGRATION

The power of theranostic nanoplatforms is substantially amplified when multiple imaging modalities are co-integrated, because single-modality imaging lacks the required sensitivity and spatial resolution and tissue penetration depth and molecular specificity to fully characterize tumors and provide real-time treatment support. MRI provides high soft-tissue contrast and excellent spatial resolution without ionizing radiation which makes it the perfect tool for tumor mapping and monitoring over time. PET provides exceptional sensitivity through its ability to detect picomolar levels which allows it to deliver complete data about how substances spread throughout the body while enabling accurate calculations of how theranostic nanoparticles move through the body. Hybrid PET-MRI scanners enable the simultaneous recording of both imaging techniques which merges molecular detection abilities with precise body structure visualization. All CT systems deliver fast and detailed three-dimensional body structure imaging, but they work best with nanoplatforms that use gold or iodine-based contrast elements.

The use of optical imaging techniques which include near-infrared fluorescence and NIR-II fluorescence and photoacoustic imaging allows researchers to conduct real-time molecular imaging studies which achieve high detection sensitivity and cellular-level detail. The photoacoustic imaging method uses laser-generated


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thermoelastic expansion to produce ultrasound signals which allow researchers to see millimeter-deep tissue while maintaining optical contrast. The fluorescence and photoacoustic signals in chemodynamic therapy theranostic systems show a direct quantitative relationship with therapeutic hydroxyl radical generation which makes these modalities suitable for real-time treatment efficacy evaluation. The ultrasound-based theranostics system uses phase-transition nanodroplets that contain perfluorocarbon compounds to provide acoustic droplet vaporization which improves image contrast while enabling high-intensity focused ultrasound (HIFU) tumor ablation through one system that responds to external stimuli.

## STIMULI-RESPONSIVE DRUG RELEASE MECHANISMS

The advanced theranostic platforms rely on stimuli-responsive drug release as their main design element which enables targeted drug delivery through specific pathological microenvironmental triggers while preventing drugs from leaking during their movement through the bloodstream. The selectivity lets doctors provide better treatment outcomes because it limits dangerous side effects while linking imaging results to drug release for continuous monitoring of drug distribution.

The pH-responsive release mechanism uses the acidic tumor microenvironment which has pH 6.0–7.0 in tumor extracellular space and pH 4.5–5.5 in endosomes/lysosomes after cellular uptake to release drugs from acid-labile linkers and protonatable polymer matrices and pH-sensitive liposomal membranes. This release mechanism serves as a standard procedure which shows high accuracy for cancer-targeting theranostic drug delivery systems.

The ROS-responsive systems use high reactive oxygen species levels found in the tumor microenvironment to deliver drugs through oxidation-based breakdown of boronate ester and thioketal and sulfide-based polymer linkages. The CDT theranostic platforms which use Fenton chemistry display their therapeutic ROS generation through ROS-activated fluorescence probes which show the connection between therapeutic activity readout and imaging signal.

The combination of thermal stimuli produced through NIR laser light and photothermal agents in the nanoplatform leads to drug release from thermosensitive liposomes and phase-change materials which create a photoacoustic imaging signal that corresponds with the current temperature thus enabling temperature-controlled drug release based on real-time thermal imaging feedback. Enzyme-responsive systems use tumor tissue protease overexpression because specific proteases (matrix metalloproteinases, cathepsins) and kinases exist in excess to cleave enzyme-sensitive peptide linkers which release therapeutic payloads that target tumors with high selectivity. The glucose oxidase (GOx)-mediated enzymatic systems create Fenton chemistry prerequisites through acid byproduct production which triggers fluorescence reporters to form a closed-loop theranostic system that connects enzyme activity with therapeutic production and imaging signal activities.

## SUMMARY TABLE — KEY THERANOSTIC NANOPLATFORM ARCHITECTURES

| Platform Type | Size Range (nm) | Imaging Modalities | Therapeutic Modalities | Drug Loading Mechanism | Key Stimuli-Response | Key Advantages | Key Limitations |
|---|---|---|---|---|---|---|---|
| Liposomes | 80–200 | MRI (SPION-loaded), Fluorescence (QD/dye-loaded), PET (radiolabeled) | Chemotherapy (DOX, PTX, CDDP), PDT, siRNA delivery | Hydrophilic core encapsulation; lipophilic bilayer intercalation | pH, temperature (thermosensitive lipids), ROS | Biocompatible, biodegradable; versatile dual hydrophilic/hydrophobic loading; EPR accumulation | Short shelf life; drug leakage; limited scalability |
| SPIONs | 5–50 | MRI (T2 contrast), | Chemotherapy | Surface conjugation; | pH (acid-labile | Strong MRI contrast; | Potential iron |


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|---|---|---|---|---|---|---|---|
| | | Dual MRI/fluorescence | (surface-conjugated), PTT (combined with shell), hyperthermia | polymer coating | linkers), magnetic hyperthermia, enzymatic | magnetic targeting; high drug conjugation capacity | toxicity; aggregation tendency; limited drug loading capacity |
| Gold Nanostructures | 10–100 | PAI, SERS, CT (X-ray contrast), Two-photon fluorescence | PTT (photothermal ablation), PDT, immunotherapy activation | Surface thiol conjugation; PEG-drug loading | NIR laser (photothermal), TME pH | Tunable LSPR; excellent photothermal conversion; versatile surface chemistry | High cost; non-biodegradable; uncertain long-term retention |
| Polymeric NPs (PLGA, PLA, chitosan) | 50–300 | MRI (Gd/Mn-loaded), Fluorescence (dye-conjugated) | Chemotherapy, gene therapy (siRNA, miRNA), immunotherapy | Encapsulation (nanoprecipitation, emulsion); surface conjugation | pH, ROS, enzyme, redox (GSH) | Biodegradable; high versatility; tunable release; excellent biocompatibility | Polydispersity; batch-to-batch variability; complex synthesis |
| Quantum Dots (QDs) | 2–10 | NIR/visible fluorescence (PL), Dual PET/optical | Conjugated chemotherapy; PDT (as photosensitizers) | Surface bioconjugation; encapsulation in carriers | Light (photodynamic activation), pH | Size-tunable emission; high photostability; multiplexing capability; excellent FRET properties | Heavy metal toxicity (Cd-based); non-biodegradable; limited clinical translation |
| Mesoporous Silica NPs (MSNPs) | 50–200 | MRI (Mn/Gd-doped or SPION-loaded), Fluorescence | Chemotherapy (high loading capacity), gene therapy, PDT | Large mesopore encapsulation (≥35% loading efficiency) | pH, ROS, enzyme, redox, light | Exceptionally high drug loading capacity; tunable pore size; easy surface functionalization | Silica persistence; potential toxicity concerns; regulatory uncertainties |
| Carbon-based (GQDs, CNTs) | 5–100 | NIR-II Fluorescence, PAI, Raman imaging | PTT, PDT, CDT, ferroptosis | Non-covalent π-π stacking; surface functionalization | NIR laser, ROS, pH | Broad light absorption; high photothermal efficiency; strong Raman signal | Potential cytotoxicity; unclear long-term biodistribution |
| Upconversion NPs (UCNPs) | 10–50 | UCL (anti-Stokes fluorescenc | PTT, PDT (NIR-activated), | Surface conjugation; silica shell | NIR light (980 nm), pH | NIR-activated deep tissue imaging; | Low quantum yield; |


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|---|---|---|---|---|---|---|---|
| | | e), PAI, MRI (Gd-doped) | chemotherapy | encapsulation | | eliminates autofluorescence background | complex synthesis; non-biodegradable |
| Hybrid/Biomimetic | 80–300 | Multimodal (MRI + PA + FL + CT combinations) | Multi-mechanism (PTT + PDT + chemo + immunotherapy) | Composite encapsulation strategies | Multiple stimuli (pH + ROS + light + enzyme) | Superior targeting; immune evasion; synergistic therapy; comprehensive imaging | Highest complexity; challenging manufacturing scale-up; rigorous safety profiling required |

## DISEASE APPLICATIONS

### 7.1 Oncology

The main field where theranostic nano systems are used for their applications focuses on cancer treatment because their EPR effect enables tumor targeting and researchers understand the TME which exists at acidic pH and has high ROS levels and excessive protease production and hypoxic conditions and clinicians need direct treatment evaluation during medical procedures. Theranostic nanoplatforms have been developed and validated preclinically across virtually all major solid tumor types — breast cancer, lung cancer, pancreatic cancer, hepatocellular carcinoma, colorectal cancer, glioblastoma, and melanoma. The new method of nanoplatform-based theranostics enables glioblastoma treatment through targeted drug delivery which crosses the blood-brain barrier and uses real-time diagnostic imaging that employs surface ligands of transferrin and anti-EGFR antibodies to achieve better tumor targeting and reduced body wide harmful effects.

### 7.2 Cardiovascular Disease

The theranostic nanoplatforms for atherosclerosis research use MRI or optical contrast agents together with anti-inflammatory and antiproliferative medications that include rapamycin and statins to create a unified system which targets activated endothelium and foam cells through VCAM-1 and other endothelial adhesion molecules. Bimodal MRI/fluorescence theranostic liposomes functionalized with the VCAM-1-targeting peptide VHP have demonstrated specific labeling of atherosclerotic plaques with simultaneous drug delivery in preclinical models.

### 7.3 Neurological Conditions and Infectious Diseases

The brain damage resulting from traumatic brain injury (TBI) treatment uses theranostic nanomaterials which deliver neuroprotective drugs through brain imaging techniques that use MRI and fluorescence to track brain damage while delivering therapeutic substances to damaged areas. In infectious disease, nanotheranostic platforms which contain antibacterial agents and diagnostic probes enable doctors to detect pathogens while monitoring treatment progress in real time which proves especially useful for antibiotic-resistant infections that require quick adjustments to treatment methods.

## CLINICAL TRANSLATION: CHALLENGES AND PROGRESS

### 8.1 Regulatory and Safety Challenges

The clinical translation of theranostic nanoplatforms encounters significant regulatory challenges because of their built-in ability to perform multiple functions. Theranostic nanosystems do not fit existing drug and imaging agent evaluation methods because they operate as three different product types which require separate regulatory pathways to obtain approval. The FDA and EMA have not created standardized rules for drug and imaging agent nanoplatforms which forces companies to assess their products through individual testing procedures that extend the time needed for product development. The primary safety issues for biocompatibility testing include non-biodegradable materials which consist of cadmium-based quantum dots and gold nanostructures and carbon nanotubes. The clinical development process nowadays prefers biodegradable materials such as PLGA polymers


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and lipid carriers and silica. All nanomaterials require thorough testing to establish their body clearance and permanent accumulation patterns throughout their entire lifespan. Researchers need to choose materials very carefully because all drug release residual nanomaterials must undergo secure body degradation and excretion.

**8.2 Manufacturing and Scalability**

Pharmaceutical engineering encounters major difficulties because it needs to achieve three goals: reproducible batch manufacturing, effective production methods, and performance assessment of multifunctional nanoplatforms. The system becomes more complex when it uses hybrid technologies that combine organic materials with inorganic materials. The new continuous-flow manufacturing methods together with microfluidic synthesis platforms create effective solutions for producing nanoplatforms at large scale while maintaining reproducibility.

**8.3 Clinical Progress**

The theranostic nano systems have reached clinical testing even though they face existing challenges. The FDA approved SPION-based formulations which include ferumoxytol for use as iron supplements and as MRI contrast agents despite their off-label application. Researchers developed radiolabelled nanoparticle systems to track drug delivery through PET imaging which currently undergoes testing in initial stages of clinical studies. The clinical success of lipid nanoparticles demonstrated in mRNA COVID-19 vaccines has substantially advanced the regulatory and manufacturing pathway for lipid-based theranostic carriers.

## EMERGING DIRECTIONS

**AI-Assisted Closed-Loop Theranostics**

The fusion of artificial intelligence and machine learning with theranostic systems has emerged as a new research area that can bring about major changes in medical practice. The analysis of real-time multimodal imaging data through AI enables adaptive and closed-loop therapeutic decision-making based on imaging-derived feedback which determines dosage adjustments and treatment schedules and design specifications for nanoplatforms. Machine learning-based bioinformatics research has already discovered new molecular pathways that exist in the tumor microenvironment, which scientists use to develop precision medicine targets for theranostic optimization.

**9.2 Immunotherapy Integration**

Researchers develop new theranostic nanoplatforms which combine immunotherapeutic agents from three different categories: immune checkpoint inhibitors and tumor vaccines and cytokine modulators. The combination of PD-1/PD-L1 inhibitors with tumor antigens through nanoplatforms which also contain radiolabeled antibodies and PET immunotracers enables researchers to conduct real-time assessments of immune activation and T-cell infiltration and immunotherapy results. The system develops a solution to an essential unmet requirement which needs early biomarkers that can assess checkpoint inhibitor effectiveness without invasive procedures.

**9.3 Multimodal and Adaptive Platform Design**

The upcoming decade will bring forth advanced theranostic platforms which will incorporate NIR-II fluorescence and photoacoustic imaging and MRI into a single system that provides different treatment methods for photothermal therapy and chemical drug therapy and immunotherapy. The systems will achieve their full potential through the integration of biodegradable nanocarrier systems and AI-based treatment customization which will create a complete personalized medical system that uses visual tracking technology.

## CONCLUSION

Theranostic nanoplatforms create a fundamental shift in medical practice because they replace traditional diagnostic procedures which occur before treatment. The theranostic system enables researchers to track drug distribution and treatment outcomes through its combined imaging and medicine delivery system which creates a complete medical system that delivers precise disease assessment and limits unwanted body effects through its controlled medicine distribution system which enables doctors to modify their treatment plans based on current medical data. This developing toolkit needs liposomes SPIONs gold nanostructures polymeric nanoparticles quantum dots and hybrid systems because each of these elements provides separate functions. The system enables multimodal imaging by combining MRI and PET and photoacoustic and fluorescence methods to deliver anatomical functional and molecular data in a new imaging system with higher resolution than before. The clinical translation process depends on ongoing teamwork between experts in materials science and pharmacology and


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medical imaging and oncology and regulatory science which must be matched with methods to create products and establish common rules. The development of AI-driven platform design with closed-loop feedback systems will enable theranostic nano systems to become standard clinical practices because doctors will use real-time molecular monitoring to assess treatment effectiveness during every therapy session.

**REFERENCES**

1. Ilerhunmwuwa NP, Sahin IH, Saeed A. Advances in multimodal imaging techniques in nanomedicine: enhancing drug delivery precision. *RSC Nanoscale.* 2024. doi:10.1039/D5NR00000X.
2. Wan Y, Liu Y, Wen W, et al. Activatable companion theranostics for dual-modality imaging-escorted pyroptosis-propelled synergistic cancer therapy. *Bioactive Materials.* 2024;54:614–630.
3. Gawne PJ, Ferreira M, Papaluca M, Grimm J, Decuzzi P. New opportunities and old challenges in the clinical translation of nanotheranostics. *Nat Rev Mater.* 2023;8:1045–1062.
4. Liu Y, Bhattarai P, Dai Z, Chen X. Photothermal therapy and photoacoustic imaging via nanotheranostics in cancer. *Chem Soc Rev.* 2019;48:2053–2108.
5. Chang D, Ma Y, Xu X, Xie J, Ju S. Stimuli-responsive polymeric nanoplatforms for cancer therapy. *Front Bioeng Biotechnol.* 2021;9:707319.
6. Carrese B, Sanità G, Lamberti A. Nanoparticles design for theranostic approach in cancer disease. *Cancers.* 2022;14:4654.
7. Gholami L, et al. Chitosan-based nanoplatform incorporating doxorubicin and SPIONs for pH-dependent drug release and MRI theranostics in glioma. *J Controlled Release.* 2023.
8. Lankoff AM, Czerwińska M, Kruszewski M. Advances in nanotheranostic systems for concurrent cancer imaging and therapy: an overview of the last 5 years. *Molecules.* 2024;29:5985.
9. Bukhari SI, Imam SS, Ahmad MZ, et al. Recent progress in lipid nanoparticles for cancer theranostics: opportunity and challenges. *Pharmaceutics.* 2021;13:840.
10. Salgueiro MJ, Zubillaga M. Theranostic nanoplatforms in nuclear medicine: current advances, emerging trends, and perspectives for personalized oncology. *J Nanotheranostics.* 2024;6:27.
11. Wilhelm S, Tavares AJ, Dai Q, et al. Analysis of nanoparticle delivery to tumours. *Nat Rev Mater.* 2016;1:16014.
12. Feng GL, Zhang JW, Zhou W, et al. Glycosylated multifunctional nanoplatform co-delivering artemisinin: synergizing NIR-responsive phototherapy with chemodynamic therapy for precision-targeted tumor theranostics. *Adv Healthcare Mater.* 2024. doi:10.1002/adhm.202403975.
13. Puccetti M, et al. Nanotheranostics in immunotherapy, gene therapy, and personalized medicine. *J Nanobiotechnology.* 2024.
14. Blanco E, Shen H, Ferrari M. Principles of nanoparticle design for overcoming biological barriers to drug delivery. *Nat Biotechnol.* 2015;33:941–951.
15. Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer nanomedicine: progress, challenges and opportunities. *Nat Rev Cancer.* 2017;17:20–37.


**DOI:** 10.46121/pspc.53.2.31

16. Ashekyan O, Shahbazyan N, Bareghamyan Y, et al. Transcriptomic maps of colorectal liver metastasis: machine learning of gene activation patterns in support of precision medicine. *Cancers (Basel).* 2023;15:3835.


**DOI:** 10.46121/pspc.53.2.31