RESEARCH PAPER

Radiology-Guided Targeted Drug Delivery: Enhancing Precision Therapeutics through Advanced Imaging Techniques

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Abstract
Radiology-guided targeted drug delivery is an emerging precision-therapeutic strategy that integrates advanced imaging, minimally invasive intervention, and targeted delivery platforms to improve drug localization and treatment monitoring. Conventional systemic therapy is often limited by nonspecific biodistribution, poor tissue penetration, premature clearance, and dose-limiting toxicity, particularly in oncology, neurological disorders, cardiovascular disease, and inflammatory conditions. Image-guided approaches address these limitations by enabling lesion localization, route planning, real-time procedural guidance, biodistribution assessment, and early response evaluation. Ultrasound, CT, MRI, fluoroscopy, PET, SPECT, and hybrid imaging systems each contribute distinct advantages for localized, regional, molecular, or theranostic delivery. Drug delivery platforms such as nanoparticles, liposomes, microbubbles, hydrogels, radioligands, and catheter-based systems further enhance site-specific therapeutic deposition and in vivo tracking. Applications include focused ultrasound-mediated blood–brain barrier modulation, CT-guided intratumoral therapy, PET/SPECT-guided radioligand treatment, nanomedicine-based carrier tracking, and locoregional therapy for solid tumors. Despite challenges related to biological heterogeneity, imaging standardization, safety, scalability, and regulatory translation, radiology-guided targeted drug delivery offers a clinically relevant pathway for individualized treatment. Continued integration of molecular imaging, theranostics, smart carriers, and quantitative monitoring may improve therapeutic precision, reduce systemic toxicity, and strengthen patient-specific treatment optimization.

Keywords: Radiology-guided drug delivery, targeted drug delivery, precision therapeutics, image-guided therapy, theranostics

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Introduction

The movement of targeted drug delivery has become one of the main strategies for precision medicine due to its aim to deliver maximum therapeutic benefit at disease sites with a minimum dose of drug to healthy tissues. Systemic administration of conventional drugs tends to give suboptimal therapeutic indices through the following reasons: the drug will be carried around in the body, it will be prematurely metabolized or excreted, and it will interact with non-target organs before reaching its pathological target. These restrictions are particularly important in oncology, inflammatory diseases, neurological diseases, and cardiovascular pathologies, where the spatial distribution of the disease, molecular variations, and the presence of barriers have a strong impact on the response to treatment. Besides biologically selective therapeutic agents, drug delivery systems are also needed to transport the drug, release it, and monitor the transport/release in space and time to achieve precision drug delivery. There has been a growing appreciation of the need for targeted delivery strategies, such as targeting by ligands, using carriers for transport, administration locally and biologically responsive

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release, for individualized therapy [1]. The capabilities of nanomedicine have also broadened the range of targeted therapeutics as it allows the design of carriers that have specific size, surface chemistry, payload capacity, circulation characteristics, and molecular specificity. The nanoparticles, liposomes, micelles, dendrimers, polymeric systems, and hybrid nanoplatforms can be engineered for the purpose of increasing drug solubility, protecting labile agents, increasing the circulation time, and increasing the selective accumulation in tissues. Such platforms would provide the opportunity to tailor delivery of therapy to the tumour phenotype, receptor expression, vascular permeability, immune microenvironment, and patient-specific pharmacokinetics in personalized medicine. These properties have made nanomedicine a potential way that can make a bridge between molecular targeting and clinical precision therapeutics [2].

Another building block for the image-guided targeted therapy is controlled drug delivery systems that control the time, amount, and location of drugs released. Maintenance of local therapeutic concentrations for a prolonged period of time, reduced dosing frequency, better adherence, and stimuli-responsive carriers and sustained-release implants are all methods that can be used to achieve this. There are advantages to these systems, especially when there is a need to minimize systemic exposure and repeated exposures are not possible. The current developments focus on smart delivery platforms that are responsive to pH, temperature, enzymes, magnetic fields, ultrasound, or even light, providing opportunities to manipulate the release by external stimuli and to monitor the release by imaging. Despite these advances, there are still several limitations to the translation of a nano-based and controlled delivery system to the clinic [3]. The accumulation of a drug at the target site can be decreased by biological barriers like mononuclear phagocyte clearance, vascular heterogeneity, dense extracellular matrix, high interstitial pressure, and limited tissue penetration. Reproducibility, long-term safety, regulatory complexity, and scalability are other key issues with manufacturing. These constraints suggest, however, that the design of the carrier is not enough to make targeted therapy successful; it must also be possible to localize the carrier, ensure delivery of the necessary material, and verify the distribution of the therapy in real time [4].

To address these challenges, targeted drug delivery via imaging technology and therapeutic administration is being developed and implemented in a single method, called radiology-guided targeted drug delivery. Over the years, interventional radiology has developed from a largely diagnostic and procedural specialty into a framework for customized therapy to access deep tissues, vascular territories, tumors, and organ-specific disease sites with minimal invasiveness. Radiology enables treatment to be tailored to the anatomy of the lesions and patient-specific disease distribution through image-guided needle placement, catheter navigation, locoregional infusion and embolization, ablation-combination approaches, and intratumoral injection [5]. The overall idea of image-guided intervention is the provision of the appropriate therapy in the appropriate location and with high accuracy. Imaging helps to minimize uncertainty in therapy by providing anatomical orientation, functional information, instrument tracking, and immediate feedback on the technical success. Each modality has its own unique strengths to bring to the delivery workflow, including ultrasound, computed tomography (CT), magnetic resonance imaging (MRI), fluoroscopy, angiography, positron emission tomography (PET), and single photon emission computed tomography (SPECT). These technologies can be used in the treatment planning, treatment navigation, target selection, monitoring, and follow-up assessment [6].

Theranostics is a particularly significant extension of the drug delivery aspects of radiology, where diagnosis and therapy are delivered under a single roof. Theranostic systems could involve several agents, for imaging, payload, and multifunctional carriers, so that the clinician can visualize biodistribution, can confirm that the agent has engaged the target, can monitor the release of the payload, and can assess response. This is very relevant when monitoring the treatment in real-time, as it is able to relate drug delivery with measurable imaging signals [7]. The association of imaging and therapy has been enhanced by the use of iron oxide nanoparticles and other image-visible nanomaterials, which enable diagnostic contrast enhancement, magnetic targeting, and therapeutic monitoring. Applications in cancer imaging have progressed from the traditional use of imaging for cancer detection to imaging for therapeutic evaluation, targeted drug delivery, and multimodality therapeutic planning with iron oxide nanoparticles. They are particularly relevant for magnetic visualization and/or magnetic influence targeting [8].

Labeled nanoparticles, radiopharmaceutical carriers, PET/SPECT tracking, and targeted radionuclide methods are other ways that nuclear medicine has helped image-guided drug delivery and have been used to significant effect. Nanoparticles for nuclear medicine applications can be multifunctional and contain therapeutic agents as well as imaging labels, which allows for a whole body biodistribution study and quantitative assessment of therapeutic agent delivery efficiency. They are more and more applicable to precision oncology and image-guided systemic therapy [9]. Systems pharmacology takes another step forward by applying imaging techniques to the understanding of the distribution of nanotherapies, their interactions with tissues, and therapeutic effects at various scales of biology. It is possible to design the nanotherapy using image-guided systems pharmacology, which can connect the behavior of carriers, characteristics of tumor microenvironment, pharmacokinetics, and therapeutic response. The field of radiology-guided targeted drug delivery is thus a cross-over area where cutting-edge imaging, nanomedicine, interventional, and systems-level analysis can combine to improve precision therapeutics [10].

Principles of Radiology-Guided Targeted Drug Delivery

Targeted delivery of drugs by radiology is the concept of combining a therapeutic carrier, imaging guidance, and patient-specific disease localization to enhance spatially accurate and therapeutic selectivity. The main concept is delivery of the drug to the pathogenic site in an effective and desired concentration with avoidance of systemic exposure and toxicity. Conventional targeted drug delivery is based on molecular affinity, the design of the carrier, access to the vascular system, and tissue permeability, while the procedural and monitoring aspects of radiology enable visualization of anatomy, delineation of target boundaries, development of the drug delivery route, and assessment of therapeutic distribution. In precision medicine, the heterogeneity of disease sites among patients and lesions, with respect to vascularity, receptor expression, tissue density, perfusion, and biological barriers, is particularly crucial for image-guided delivery.

This concept is demonstrated by the magnetically controlled nanocarriers, which feature a drug payload and a platform that is detectable by imaging methods, enabling precision cancer therapy and theranostic tracking of the nanocarriers [11]. This concept is further extended by the introduction of I-GDT (image-guided diagnosis and therapy), which combines the characterization of the lesion through imaging with the execution of the minimally invasive therapy based on the lesion characteristics to adapt treatment to the anatomical and functional characteristics of the lesion [12]. Another advantage of theranostic pretargeting platforms is that they can also be used to restrict therapeutic delivery by allowing specificity to be separated from therapeutic delivery, which is beneficial for cancer therapy [13]. In this context, nanoparticles can be used in molecular imaging to increase contrast, facilitate early diagnosis, and allow the simultaneous delivery of therapeutic agents [14].

Radiology-guided delivery thus takes place in four interrelated steps: target identification, route planning, controlled therapeutic deposition, and post-delivery monitoring. The use of image-guided intervention optimizes the accuracy of the procedure, minimizing uncertainty of targeting and delivery. To this end, image-guided systems pharmacology can be used to connect the biodistribution of the drugs, the response of the tissues, and the therapeutic response at the biological level. Table 1 suggests the core principles that support radiology-guided targeted drug delivery.

Table 1. Core Principles of Radiology-Guided Targeted Drug Delivery

Principle	Description	Role in radiology-guided delivery	Representative application	Reference
Target identification	Defines the diseased tissue, lesion boundary, and biologically relevant target before therapy	Supports the accurate selection of the therapeutic site and reduces nonspecific treatment	Imaging-based localization of tumors or pathological tissue before targeted delivery	[1]
Image-based treatment planning	Uses anatomical and functional imaging to determine the safest and most effective delivery route	Improves procedural planning by mapping lesion size, location, vascularity, and surrounding structures	Planning needle, catheter, or focused-energy delivery pathways	[6]
Site-specific therapeutic delivery	Directs the therapeutic agent toward the intended pathological site rather than relying only on systemic circulation	Enhances local drug concentration and reduces exposure of normal tissues	Magnetically controlled nanocarriers for cancer precision medicine	[11]
Procedural guidance	Uses real-time or near-real-time imaging to guide instruments or therapeutic systems during delivery	Improves targeting accuracy and technical success during minimally invasive procedures	Image-guided diagnosis and therapy using radiological navigation systems	[12]
Molecular targeting	Uses disease-specific molecular markers to improve the selective localization of therapeutic agents	Allows therapy to be adapted according to receptor expression or tumor biology	Pretargeted theranostic drug delivery in cancer precision medicine	[13]
Imaging-visible carriers	Incorporates contrast or imaging-active components into delivery systems	Allows visualization of carrier localization, biodistribution, and treatment delivery	Nanoparticles used for molecular imaging and targeted therapeutic transport	[14]
Post-delivery monitoring	Assesses whether the drug or carrier reached the target and evaluates early tissue response	Supports adaptive treatment decisions and response evaluation	Imaging-guided systems pharmacology for monitoring nanotherapy delivery and action	[10]

Conventional Drug Delivery and Rationale for Imaging Guidance

The conventional drug delivery system is still restricted by inadequate site specificity, unstable bioavailability, premature degradation of the drug, systemic clearance, and toxicity at high doses. Systemic administration can lead to systemic distribution of drugs in normal and diseased tissues, which causes a low therapeutic index and hence high side effects. These restrictions are particularly important for poorly soluble drugs, nucleic acid therapeutics, anti-cancer drugs, and biologics in which effective therapy depends on adequate drug concentrations at a specific pathological site. Engineered carriers have boosted the efficiency of delivery, but clinical applications are still limited due to heterogeneous vascular permeability, immune clearance, limited tissue penetration, and variable target accumulation. The barriers have been tackled by controlled drug delivery systems, which aim to control the drug release rate and ensure the drug remains at a therapeutic level for an extended period of time, although there are still many platforms to be developed where drug localization and confirmation of deposition are crucial. There are also challenges associated with the stability, toxicity, reproducibility, manufacturability, and regulatory translation of nano drug delivery systems.

The possibility of overcoming these limitations exists in the image-guided drug delivery, which is the association of therapeutic administration with anatomical and functional visualization. Theranostics and image-guided drug delivery platforms combine therapy and diagnosis in one system, enabling the localization of the disease, tracking of the distribution of the carriers, and the assessment of the therapeutic response [15]. The theranostic use of iron oxide nanoparticles (IONPs) guided by MR imaging can be used as a diagnostic aid, navigation, targeted delivery, and follow-up assessment [16]. For focused ultrasound therapy, the concept is further extended to include the ability to deposit energy and release drugs, all without touching the patient, using the focused ultrasound beam and an image-guided approach [17]. MR-guided interventions are well-suited for anatomical areas where treatment delivery is difficult, as they allow for real-time guidance and planning, and high soft-tissue contrast [18]. Therefore, imaging guidance is crucial to better localization, safety, and therapeutic efficiency.

Ultrasound-Guided and Focused Ultrasound-Mediated Drug Delivery

Spatial control, tissue penetration, and stimulus-responsive therapeutic release are important pathways that can be enhanced by ultrasound-guided and focused ultrasound-mediated drug delivery, respectively. Ultrasound can allow for real-time visualization, procedural flexibility, no ionizing radiation use, and the ability to be compatible with contrast agents, which allows for local injections, vascular targeting, and external triggering. For targeted systems, ultrasound can not only be used as an imaging agent; it can also be used as an active therapeutic agent that can alter tissue permeability or release drugs from agents that are responsive to ultrasound. This functionality is related to the concept of controlled delivery, where drug delivery is controlled based on site, time, and therapeutic requirement. Because lipid microbubbles are capable of increasing acoustic cavitation and thus increasing the local permeability of blood vessels, they have been studied extensively as ultrasound-responsive vehicles. In focused ultrasound-induced blood–brain barrier opening, the therapeutic agent can be introduced into the brain tissue in a spatial way by temporarily opening endothelial tight junctions [19]. The ultrasound-targeted microbubble destruction system is also used to achieve localized delivery of drugs into the tumor tissue by mechanically disrupting microbubbles at the targeted area and enhancing vascular permeability, thereby promoting the delivery of therapeutic agents into the tumor microenvironment [20]. Experimental studies in liver tumors have shown the ability of low-intensity focused ultrasound to mediate the delivery of drugs in the region corresponding to the location of the tumor, thereby raising the possibility of solid-organ cancer treatment [21]. Targeted drug delivery has also been investigated with the use of high-intensity focused ultrasound, which has the potential to focus the acoustic energy at specific tissue depths and induce thermal or mechanical fields that promote drug release and tissue uptake [22]. This is similar to other image-guided therapeutic platforms involving diagnosis, delivery, and monitoring of therapeutic agents. Focused ultrasound therapy is therefore able to bridge the gap between imaging and controlled drug activation, without requiring invasive procedures. Table 2 summarizes ultrasound-guided and focused ultrasound-mediated drug delivery approaches.

Table 2. Ultrasound-Guided and Focused Ultrasound-Mediated Drug Delivery

Ultrasound-based approach	Mechanism of drug delivery	Imaging or therapeutic role	Representative application	Reference
Ultrasound-guided localized delivery	Uses real-time ultrasound visualization to guide needle placement or local therapeutic administration	Provides non-ionizing, real-time procedural guidance for targeted delivery	Localized drug administration in accessible tumors or soft-tissue lesions	[36]
Lipid microbubble-assisted delivery	Uses circulating lipid microbubbles to enhance acoustic cavitation and	Supports focused ultrasound-induced blood–brain barrier opening	Targeted delivery of therapeutic agents across the blood–brain barrier	[19]

	transiently increase vascular permeability			
Ultrasound-targeted microbubble destruction	Destroys microbubbles at the target site to increase local permeability and drug deposition	Enables spatially localized release or uptake within tumor tissue	Localized drug delivery into the tumor microenvironment	[20]
Low-intensity focused ultrasound	Concentrates acoustic energy at the target tissue without requiring invasive access	Enhances localized therapeutic accumulation through mechanical bioeffects	Localized drug delivery for liver tumors	[21]
High-intensity focused ultrasound	Uses focused acoustic energy to induce thermal or mechanical effects that promote drug release or tissue uptake.	Provides externally controlled, non-invasive targeting	Targeted drug delivery using HIFU-mediated tissue effects	[22]
Focused ultrasound-triggered controlled release	Activates drug release from responsive carriers using acoustic energy	Links controlled drug delivery with external image-guided stimulation	Stimulus-responsive therapeutic release at selected tissue sites	[17]
Microbubble-enhanced controlled delivery	Combines ultrasound-responsive carriers with controlled release principles	Improves spatial and temporal regulation of drug delivery	Site-specific delivery where release timing and localization are critical	[3]

MRI-Guided Focused Ultrasound for Blood–Brain Barrier Modulation and CNS Drug Delivery

Because of its ability to deliver acoustic energy noninvasively while providing high-resolution anatomical visualization, magnetic resonance imaging (MRI) based focused ultrasound (FUS) has emerged as an important platform for targeted delivery of drugs to the central nervous system (CNS). In the case of glioblastoma, brain metastases, and other neurological diseases, the blood–brain barrier prevents many chemotherapeutics, antibodies, nanoparticles, and gene-based agents from reaching brain tissue, and as a result, the drugs are not effective. MR guidance overcomes this limitation by allowing for accurate location of targets, planning treatment, monitoring tissue temperature using MR thermometry, and monitoring the impact of the procedure on the tissue in the post-procedural stages. Previously, MRI-guided intervention schemes were introduced and demonstrated the usefulness of MRI to visualize soft tissue and to guide therapy in an anatomically sensitive area.

Presently, the data indicate that with the introduction of microbubbles into the circulation, focused ultrasound can transiently and reversibly disrupt the blood–brain barrier in a spatially selective manner, thereby improving the penetration of drugs. For brain metastasis, the technique has been looked at for the possibility of enhancing the intratumoural delivery of systemic anticancer drugs into intracranial metastatic lesions, where systemic therapy is limited by poor permeability and inadequate drug exposure. In addition, MR-guided FUS could be applied to targeted drug or molecular delivery, such as targeted chemotherapy, targeted immunotherapy, targeted nanoparticles, and targeted molecular agents, as suggested by reviews on brain tumor therapy [25]. More recently, in glioma treatment, its ability to cross biological barriers, increase therapeutic accumulation, and precision in the treatment of difficult-to-treat infiltrative tumors has been emphasized [26].

This method builds on a previous idea of ultrasound-mediated delivery with microbubbles to enhance tissue permeability and ultrasound-mediated targeting with focused ultrasound. Thus, MRI-guided focused ultrasound is a converging approach to CNS precision therapeutics guided by radiology. Figure 1 illustrates MRI-guided focused ultrasound for blood–brain barrier disruption and targeted drug delivery.

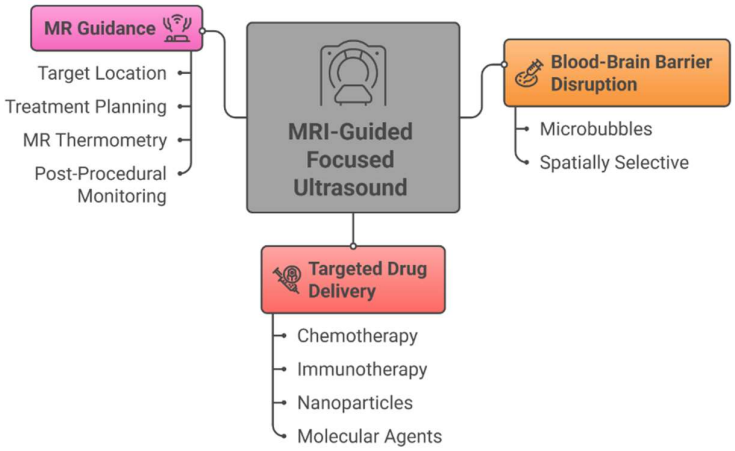

Figure 1. MRI-Guided Focused Ultrasound for Blood–Brain Barrier Disruption and Targeted Drug Delivery

CT-Guided and Image-Guided Percutaneous Localized Drug Delivery

The CT-guided and image-guided percutaneous localized drug delivery are methods that enable direct access to deep lesions, which are hard to get to via systemic routes. Such approaches are especially significant for the delivery of therapies such as drugs, cells, hydrogels, gene-based agents, or immune-modulating agents to a specific anatomic site. Interventional radiology can aid this process by using lesion mapping, trajectory planning, needle placement, and delivery verification, as well as by performing a safety assessment post-procedurally. In addition to being a localized approach, this strategy is mostly in line with personalized interventional radiology, as treatment can be tailored in relation to the size, location, vascularity, and proximity of the lesion to critical structures. Image-guided intervention also enhances the confidence of the procedure for making accurate targets and reducing uncertainty during therapeutic administration [6].

CT-guided access has been reported as technically feasible and safe for delivering gene-modified cellular immunotherapy in metastatic non-small cell lung cancer, [27] – a testament to the potential of CT-guided access for complex anticancer biologics. In addition, ultrasound-guided intratumoral therapy offers real-time visualization for directly injected therapy, and technical benefits in tumors that are accessible and logistical benefits for repeated administration [28]. In addition to oncology, the use of thermosensitive simvastatin/poloxamer hydrogel for percutaneous intraosseous injection has been demonstrated to treat localized bone formation, which is another potential application of image guidance in the delivery of depot-based drugs for skeletal disease [29]. Nanomaterials-based CT contrast agents are also used in this application and enhance the imaging of lesions, tracking of the carrier, and image-guided therapeutic monitoring [30].

The MRI-guided intervention principles are still applicable since high-contrast imaging can be used to complement CT or ultrasound if soft tissue definition is desired [18]. Therefore, CT-guided and multimodal percutaneous delivery are viable approaches of precision therapeutics that are guided by radiology. Table 3 presents CT-guided and image-guided percutaneous localized drug delivery strategies.

Table 3. CT-Guided and Image-Guided Percutaneous Localized Drug Delivery

Image-guided delivery approach	Mechanism of localized delivery	Imaging role	Representative application	Reference
CT-guided transthoracic intratumoral injection	Delivers therapeutic agents directly into tumor tissue through percutaneous needle access	Supports lesion localization, trajectory planning, and safe needle placement	Gene-modified cellular immunotherapy in metastatic non-small cell lung cancer	[27]
Ultrasound-guided intratumoral administration	Uses real-time sonographic visualization to guide direct tumor injection	Enables dynamic needle visualization and repeatable local administration	Directly injected therapies in accessible solid tumors	[28]
CT-guided intraosseous injection	Delivers therapeutic depot formulations into bone through image-guided percutaneous access	Confirms skeletal target localization and accurate intraosseous placement	Thermosensitive simvastatin/poloxamer hydrogel for vertebral bone formation	[29]

Nanomaterial-enhanced CT-guided therapy	Uses CT-visible nanomaterials to improve visualization and therapeutic tracking	Enhances contrast, lesion definition, and image-guided treatment monitoring	CT contrast nanomaterials for image-guided therapy	[30]
Interventional radiology-guided localized therapy	Applies minimally invasive access to lesion-specific treatment delivery	Integrates planning, targeting, delivery confirmation, and safety assessment	Personalized local treatment adapted to lesion anatomy and patient risk	[5]
Image-guided procedural navigation	Uses imaging to reduce uncertainty during therapeutic administration	Improves technical precision and first-pass targeting accuracy	Needle- or catheter-based delivery in deep anatomical sites	[6]
MRI-complemented percutaneous delivery	Uses MRI when high soft-tissue contrast is needed alongside CT or ultrasound	Improves visualization of anatomically complex or soft-tissue targets	Multimodal planning for localized precision delivery	[18]

PET-, SPECT-, and Molecular Imaging-Guided Drug Delivery

PET-, SPECT-, and molecular imaging guided drug delivery will provide information on function and quantitative data beyond what can be gained from anatomical imaging. The modalities are critical for precision therapeutics, enabling identification of molecular targets, receptor expression, whole-body biodistribution, pharmacokinetics measurement, and assisting in treatment selection based on imaging. In contrast to local delivery using either CT or ultrasound guidance, nuclear imaging may assess target lesions and off-target organs throughout the body, particularly where systemic strategies are being used to deliver targeted therapies and theranostic platforms. This is in line with theranostic drug delivery, where diagnostic imaging and therapeutic agents are coupled together to allow treatment delivery and also to track therapeutic response.

Targeted radionuclide therapy and emerging PET imaging agents in oncology, using targeted visualization and treatment planning with radionuclides, have increased the applications in cancer [31]. PET and SPECT are also useful in enhancing the localization of disease, tracking therapeutic agents, and assessing biological responses following PDT [32]. Application-driven imaging agent design has demonstrated that proper design of an imaging agent for image-guided therapy requires it to possess characteristics of the tracer, biology of the target, agent clearance, and therapeutic goal [33]. The following examples illustrate the relevance of functional molecular imaging in nephro-urology and how PET-based and molecular imaging approaches can contribute to the characterization of the disease, selection of patients, and future theranostic applications [34].

Multifunctional nanoparticles employed in nuclear medicine can carry therapeutic agents, together with an imaging label, and thus provide the possibility to monitor delivery systems in vivo. Further, image-guided systems pharmacology enhances the interpretation process by relating the imaging signals to the distribution of the drug and therapeutic activity. Thus, the delivery of these treatments guided by PET-, SPECT-, and molecular imaging is a key direction for precision, measurable, and adaptive treatment for the individual. Figure 2 shows the integration of imaging modalities, molecular targets, and drug delivery strategies for precision therapeutics.

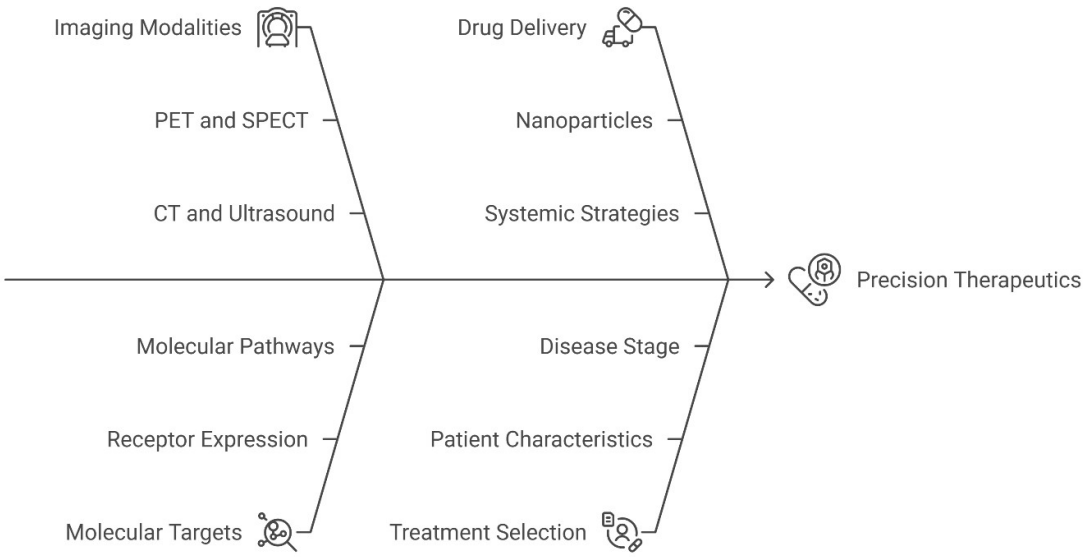

Figure 2. Integration of Imaging Modalities, Molecular Targets, and Drug Delivery Strategies for Precision Therapeutics

Nanomedicine and Image-Trackable Drug Delivery Systems

The introduction of nanomedicine and image trackable drug delivery systems offers a multi-faceted way to integrate the transport of therapeutic cargo, visualization of drugs for diagnostics, and treatment monitoring. Nanocarriers can be clinically loaded with chemotherapeutic drugs, genes, proteins, radionuclides, photosensitizers, and/or immunomodulatory agents and can contain labels for imaging by MRI, CT, PET, SPECT, ultrasound, and/or optical imaging. This dual diagnostic-therapeutic function is especially useful for precision medicine, where the different accumulation, release, and biological response of the drugs can differ significantly from patient to patient and lesion to lesion. Nanomedicine, therefore, can also be used to facilitate personalized treatment by monitoring whether a therapeutic nanocarrier is able to reach the target site before or during therapy.

The use of magnetic nanoparticles for drug delivery is particularly significant in cancer therapy, where external magnetic forces can be used to direct the nanoparticles to the target site. The nanoparticles are visible on MRI and can be used to improve targeted delivery. These systems can enhance the drug concentration at the tumor location and allow image-guided evaluation of the drug delivery [35]. The field is also advancing through the ability to visualize drugs and molecules via ultrasound, to deliver them to target areas, and to guide therapeutic interventions, such as via contrast agents, microbubbles, and acoustically activated platforms, which are all examples of technologies from the ultrasound community [36]. The use of imageable carriers to track the release of drugs by means of temperature is another example of the use of MRI visible liposomal contrast agents for controlled and spatially localized delivery [37]. The clinical potential of liposomes is very wide-ranging, as the potential for using liposomes to enhance pharmacokinetics, decrease toxicity, and facilitate image-guided drug delivery, by contrast or radionuclide labeling, has been demonstrated [38].

These systems are based on the principles of targeted delivery, carrier engineering, and image-guided pharmacology, which are more widely known. They also possess the ability to overcome chronic translational problems in nanodrug delivery, such as non-uniform biodistribution, poor tissue penetration, and lack of delivery verification. Therefore, image-trackable nanomedicine is an important stepping stone towards therapeutic design and measurable clinical delivery. Table 4 outlines nanomedicine and image-trackable drug delivery systems.

Table 4. Nanomedicine and Image-Trackable Drug Delivery Systems

Image-trackable delivery system	Imaging compatibility	Drug delivery function	Representative application	Reference
Magnetic nanoparticles	MRI-based visualization and magnetic targeting	Support tumor-directed drug transport and image-guided carrier localization.	Targeted and image-guided cancer therapy	[35]
Ultrasound-responsive agents	Ultrasound imaging and acoustically activated delivery	Enhance vascular permeability, carrier	Ultrasound-mediated drug delivery and image-guided therapy	[36]

		activation, and localized drug release		
MRI-visible liposomal contrast agents	Magnetic resonance imaging	Enable visualization of liposomal distribution and temperature-induced release.	Monitoring thermosensitive image-guided drug delivery	[37]
Liposomal drug delivery systems	MRI, PET, ultrasound, and other labeling-compatible modalities	Improve drug solubility, circulation time, pharmacokinetics, and controlled release	Clinical and potential image-guided drug delivery applications	[38]
Engineered nanocarriers	Multimodal imaging depending on incorporated contrast labels	Carry therapeutic payloads while permitting delivery tracking	Precision nanomedicine and personalized drug delivery	[2]
Targeted drug delivery nanoparticles	Imaging-compatible molecular or surface-functionalized platforms	Improve site-specific accumulation through carrier engineering	Targeted drug delivery strategies for precision medicines	[1]
Nano drug delivery systems	Imaging-compatible carrier platforms under translational development	Support therapeutic transport, but require verification of biodistribution and target deposition	Evaluation of nanodrug delivery potential and limitations	[4]

Theranostics and Multimodal Molecular Imaging Platforms

Theranostics and multimodal molecular imaging platforms are a significant expansion of the development of targeted drug delivery via radiology, as they combine detection, delivery, release, and feedback with a single platform. In this context, the same platform can be used to carry an imaging and a therapeutic payload, enabling clinicians to assess if the agent is able to reach the target tissue, estimate its biodistribution, and track therapeutic response. In the context of precision medicine, patient-specific pharmacokinetics, lesion biology, and target expression are all critical factors to consider when making treatment decisions. While conventional nanomedicine can enhance delivery, image-visible theranostic systems provide measurable feedback that helps to guide the use of personalised treatment.

Stimuli-responsive nanocarriers are at the heart of this, as they have the ability to release drugs upon the action of an internal or external stimulus such as pH, enzymes, temperature, magnetic fields, ultrasound, or light. A combination of tumor imaging, controlled treatment, and theranostic monitoring in a single design can be integrated into such systems [39]. The targeted nanotheranostics combine the use of a pre-clinical MRI and CT for molecular imaging and therapy, supporting platforms for both imaging and therapy of advanced pathological sites [40]. Whole body molecular tracking, quantitative biodistribution evaluation, and radionuclide-linked therapeutic planning are further facets of personalized theranostics using nanoparticles for SPECT and PET imaging [41]. Molecular imaging in nanotechnology offers a more solid foundation for the application of nanoparticles as diagnosis and treatment tools, including providing signals for imaging to assess target engagement and treatment response.

These platforms are based on the principles underlying theranostic systems, multifunctional nanoparticles (MNPs) based on nuclear medicine and image-guided systems pharmacology. The targeted delivery becomes a measurable, adaptive, and individualized therapeutic process when it comes to theranostic multimodal imaging. Figure 3 illustrates the workflow of theranostic and multimodal molecular imaging platforms for targeted drug delivery.

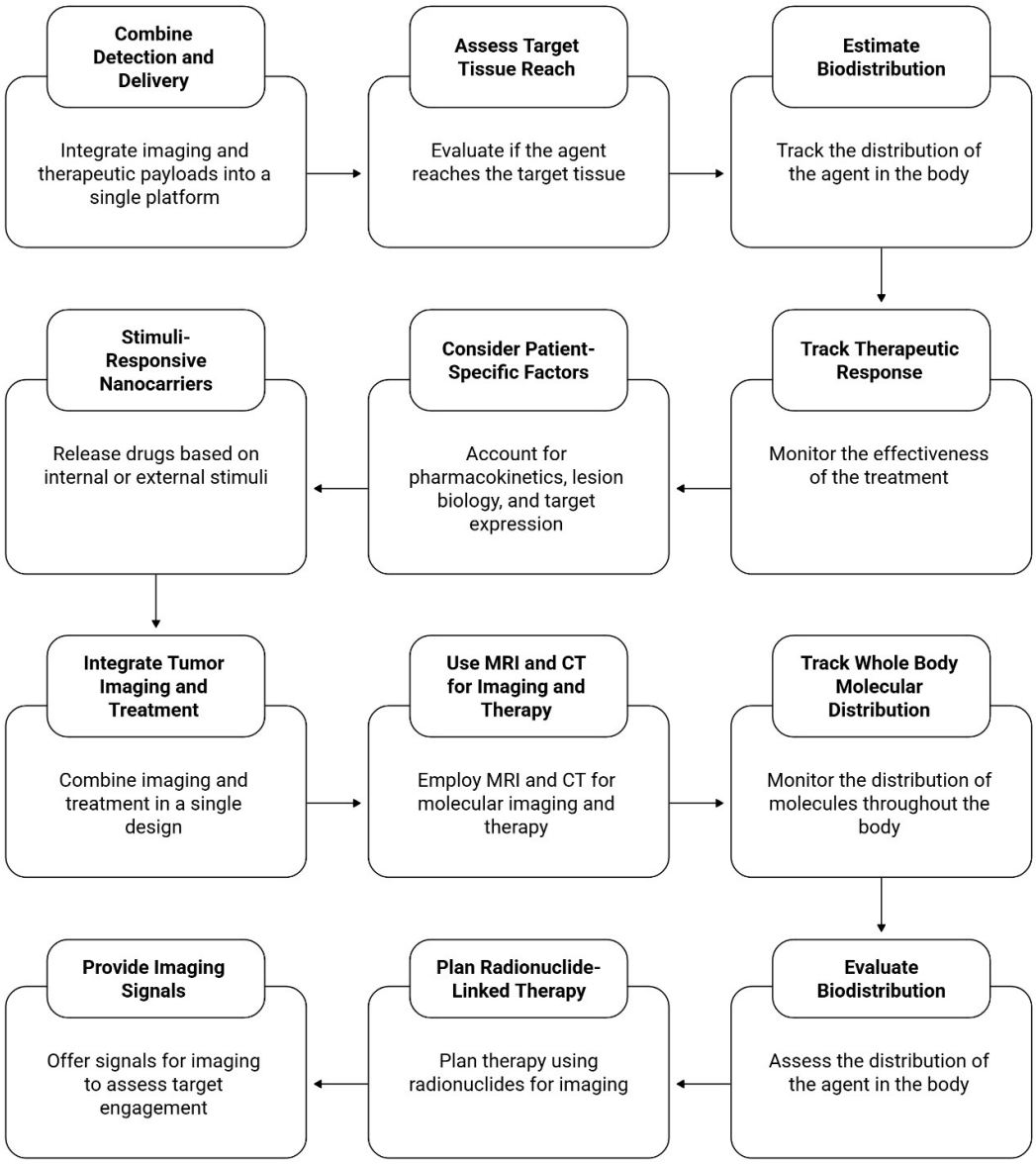

Figure 3. Workflow of Theranostic and Multimodal Molecular Imaging Platforms for Targeted Drug Delivery

Image-Guided Locoregional Therapy in Hepatocellular Carcinoma and Primary Liver Tumors

One of the most important clinical uses for the radiology-guided targeted delivery of drugs is image-guided locoregional therapy, which is mainly utilized for primary liver cancers, such as hepatocellular carcinoma. Liver is an ideal organ for locoregional intervention due to the dual vascularity, tumor arterialization, and segmental anatomy enabling selective catheter-directed or percutaneous treatment. The strategy of locoregional is to try to maximize the amount of therapeutic exposure in the tumor-bearing liver and minimize systemic toxicity. This strategy is in line with the general concept of personalized interventional radiology, which tailors treatment to the individual patient's tumor load, vascular anatomy, liver function, and risk.

Transarterial chemoembolization (TACE), radioembolization, ablation, and intra-arterial drug infusion, as well as combination modalities, have been recently developed for image-guided locoregional therapy of hepatocellular carcinoma (HCC) [43]. These methods involve imaging to assess the extent of the tumor, to map the supply vessel to the tumor, to assist in positioning the catheter for the procedure, to verify that the emboli or therapy were distributed properly, and to monitor the necrosis seen after treatment. In selected patients, image-guided percutaneous locoregional therapies provide additional options for hepatocellular carcinoma (HCC) by offering the ability to directly ablate the tumor, target injections, and achieve minimally invasive local control [44]. Improvements in imaging, device technology, and the proper sequencing of therapies have enhanced the targeting of locoregional therapy in primary liver tumors, and the use of systemic

therapy has been integrated [45]. Conventional transarterial chemoembolization, in which the catheter is inserted into the artery supplying the tumor, is an excellent example of the need for precise targeting of the arteries, as such a technique allows exposure of the tumor with the greatest drug concentration while avoiding exposure of the non-tumoral liver parenchyma [46].

The methods are based on image-guided intervention principles, which focus on good targeting and treatment verification. They also fit the image-guided therapeutic systems that involve local delivery of the therapeutic agents, imaging feedback, and adaptive control during the procedure to enhance the specificity of the therapy. The image-guided locoregional liver therapy is thus a well-established paradigm of precision therapeutics guided by images. Thus, image-guided locoregional liver therapy is a model of precision therapeutics guided by images that has become mature.

Image-Guided Theranostic Platforms for Solid Tumor Management

Diagnostic localization, molecular characterization, therapeutic delivery, and response monitoring in a single treatment platform have made image-guided theranostic platforms more and more relevant to the management of solid tumors. Therapeutic response in solid tumors is greatly affected by the characteristics of the tumor vessels, receptor expression, stromal density, perfusion heterogeneity, and regional penetration of the drugs. Imaging-guided theranostic systems aim at overcoming these variables by enabling the clinician to visualize the extent of the tumor, determine the expression of the target, choose the most convenient delivery method, and track the localization of the therapeutic agent during or after therapy. Imaging may have a role to play in a variety of precision models for colorectal cancer, such as magnetic resonance imaging-guided and targeted theranostics, which are used for tumor detection, molecular targeting, drug-carrier tracking, and treatment evaluation [47].

Nanoplatforms are another powerful tool in solid tumor theranostics that combine early diagnosis with targeted drug delivery. These systems can be modified to deliver a therapeutic payload, increase the imaging contrast, and deliver selective accumulation within the malignant tissue [48]. Near-infrared fluorescence imaging also plays a role in the management of solid tumors through sensitive visualization of tumor margins, lymphatic spread, molecular probes, and image-guided localization in surgical or minimally invasive procedures [49]. Theranostic carriers are used in interventional oncology to facilitate tumour localization, intraprocedural guidance, and delivery of localized therapy, which is a practical link between imaging and therapeutic intervention [50].

These methods are based on the principles of image-guided drug delivery that uses imaging to verify therapeutic distribution and localization of the target. They are also consistent with multimodal nanotheranostic approaches in which molecular imaging and therapy would be used and integrated for the purpose of personalized treatment planning. Finally, image-guided systems pharmacology can facilitate understanding of the relationship between imaging signal and biodistribution and therapeutic action to aid interpretation of solid tumor responses.

Limitations and Future Directions

The translation of targeted drug delivery to the clinic is hindered by biological, technical, and clinical challenges. Heterogeneity, abnormal permeability of blood vessels, high interstitial pressure, tumor clearance by immune cells, dense extracellular matrix, and poor penetration of barriers (blood–brain barrier) are factors that can lead to reduced accumulation of drugs within the tumors. Spatial resolution, visibility of the carrier, dose quantification, radiation exposure, safety of the contrast agents, complexity of the procedure, and reproducibility of the procedure between institutions also present challenges for imaging-guided systems. Nanomedicine-based platforms, however, need better proof of long-term safety, increased scalability, approval from regulatory bodies, and consistent clinical benefits. Standardized imaging protocols, quantitative biomarkers, multimodal image tracking, personalized dosimetry, and adaptive treatment planning are areas of future research for development. AI and radiomics could enhance lesion segmentation, treatment-route selection, prediction of treatment response, and patient stratification. In the future, precision, safety, and therapeutic monitoring in clinical practice can be enhanced by additional smart stimuli-responsive carriers, theranostic nanoparticles, robotic navigation, and integrated platforms of PET/MRI or MRI-guided focused ultrasound.

Conclusion

The use of radiology-guided targeted drug delivery is one of the significant advances in precision therapeutics that combines imaging diagnosis, procedure guidance, localized delivery of drugs, and drug monitoring into one clinical plan. Use of advanced imaging techniques (ultrasound, computed tomography, magnetic resonance imaging, PET, SPECT, fluoroscopy, and hybrid imaging systems) enhances lesion localization, route planning, drug deposition, biodistribution assessment, and good response evaluation. Such capabilities are especially important in oncology, neuro-oncology, interventional radiology, and theranostics, where disease heterogeneity and complexity often compromise the success of traditional systemic therapy. The delivery of therapeutic agents can be selectively targeted and their behaviour within living tissues monitored by the use of additional modalities such as nanoparticles, liposomes, microbubbles, radioligands, hydrogels, and catheter-based systems. Though there remain challenges with biological variability, imaging standardization, clinical translation, and safety, imaging-guided delivery is a feasible route to more personalized, measurable treatment. The advent of new molecular imaging, smart carriers, quantitative biomarkers, artificial intelligence, and minimally invasive technologies could further bolster its presence in the healthcare system. The

approach has good prospects to enhance therapeutic accuracy, minimize toxicity, and aid patient-specific therapy optimization as a whole.

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