A Survey of Targeted Drug Delivery and Molecular Imaging Techniques: MRI, PET, Image-Guided Therapy, and Theranostics

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Abstract

This survey explores the advancements in targeted drug delivery and molecular imaging technologies, emphasizing their transformative impact on diagnostics and therapeutics. Key technologies such as multiparametric MRI (mpMRI) and diffusion-weighted imaging have enhanced diagnostic precision, particularly in oncology by improving tumor characterization and reducing false positives. The integration of nanotechnology, including programmable lipid nanoparticles (LNPs) and versatile hydrogels, has significantly advanced drug delivery systems, despite challenges in design complexity and regulatory compliance. Moreover, AI techniques have further enhanced diagnostic capabilities, as demonstrated in brain tumor classification using multimodal AI applications. This survey also highlights the role of molecular imaging in supporting personalized medicine by providing insights into tumor biology and the tumor microenvironment (TME), thereby informing therapeutic decisions. The integration of theranostics, combining diagnostic and therapeutic functions, offers real-time monitoring and dynamic adjustment of treatments, enhancing precision medicine. Despite existing challenges in integration, standardization, and biocompatibility, these technologies promise to enhance patient outcomes across various medical disciplines. As research continues to evolve, these innovations are expected to further advance precision medicine, improving diagnostic accuracy and therapeutic efficacy. Overall, the advancements in targeted drug delivery and molecular imaging are pivotal for the evolution of precision medicine, offering more effective and personalized healthcare solutions.

1 Introduction

1.1 Significance of Advanced Medical Technologies

The evolution of medical technologies has profoundly transformed healthcare, particularly through improvements in diagnostic accuracy and therapeutic effectiveness. In oncology, advanced imaging modalities and molecular diagnostics have revolutionized practices. For example, glioma diagnosis, traditionally reliant on invasive methods, has benefited from innovations like force-detected nuclear magnetic resonance (NMR), offering non-invasive alternatives that enhance tumor characterization. Similarly, multiparametric MRI (mpMRI) has improved breast cancer diagnostics by integrating various functional MRI parameters, surpassing the limitations of dynamic contrast-enhanced MRI (DCE-MRI) [1].

In neurodegenerative diseases such as Parkinson's, the complexity of anatomical structures has spurred the development of AI-driven diagnostic algorithms, improving accuracy and efficiency. Pediatric neuro-oncology, which addresses brain and spinal cancers—significant causes of cancer-related mortality in children—has also seen advancements in imaging technologies, though the adoption of clinical decision-support systems remains limited [2].

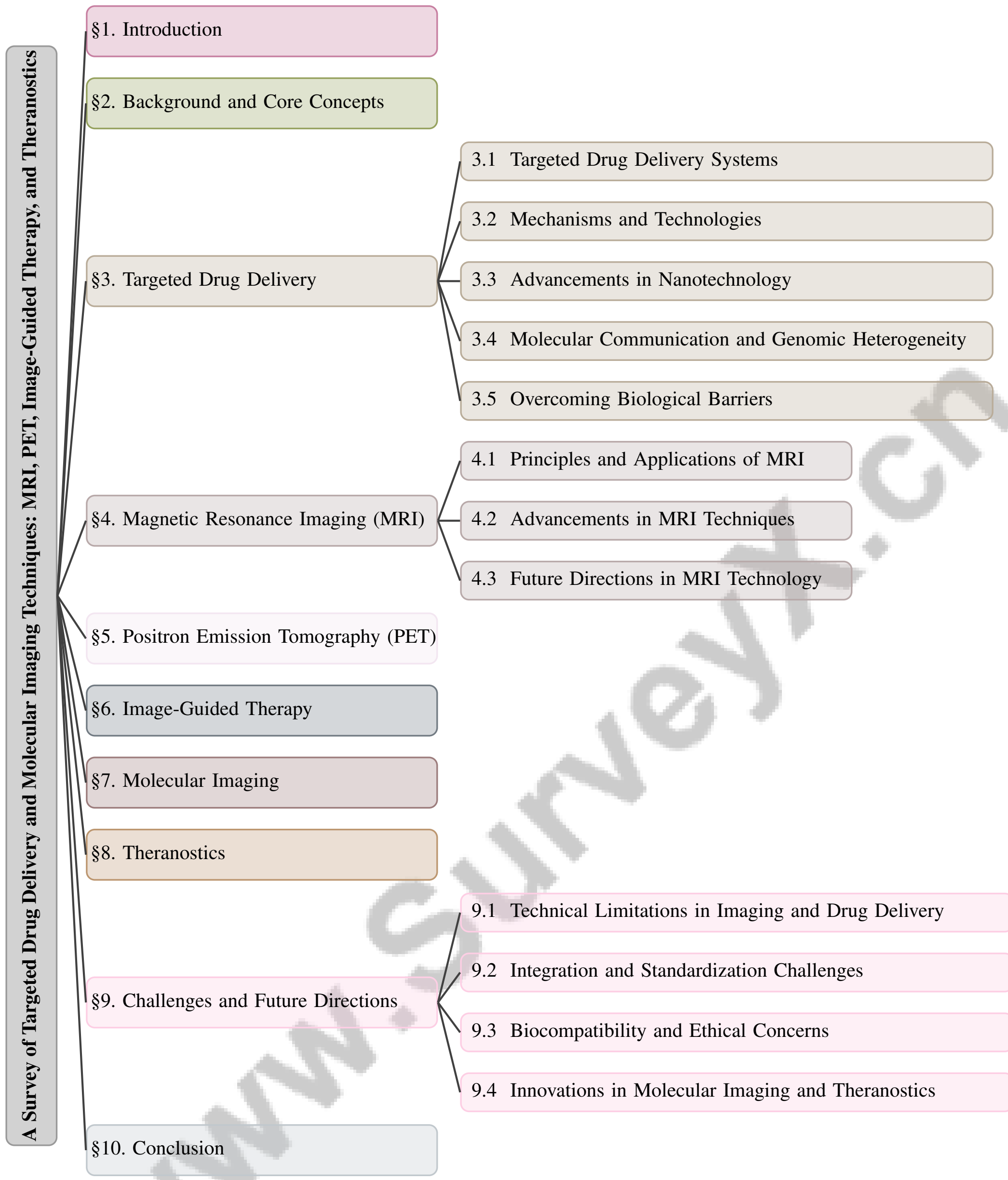


Figure 1: chapter structure

Cardiovascular and congenital heart diseases (CHD) have similarly gained from technological innovations that enhance diagnostic precision and therapeutic interventions [3]. In glioblastoma, advanced MR scans have improved predictions of survival times, underscoring the critical role of these technologies in patient management [4].

The rising incidence of breast cancer, affecting around 300,000 women in the U.S. in 2023, highlights the need for precise grading to inform diagnosis and treatment strategies. Advanced imaging technologies are essential for determining the Scarff-Bloom-Richardson (SBR) grade, crucial for evaluating responses to chemotherapy [5]. As medical technologies advance, they promise more personalized and effective treatment strategies, ultimately improving patient outcomes across various medical fields.

1.2 Role of Targeted Drug Delivery

Targeted drug delivery systems represent a significant advancement in modern medicine, enhancing therapeutic efficacy while minimizing systemic toxicity. Particularly relevant in cancer therapies, these systems address challenges related to drug toxicities and resistance [6]. Nanoparticle-based delivery systems have markedly improved the precision of drug targeting, ensuring that therapeutic agents are delivered specifically to diseased sites, thus reducing adverse effects and enhancing patient outcomes [7].

The synergy between targeted drug delivery and imaging technologies has further expanded its applicability. Techniques such as 'virtual biopsy' leverage these systems to improve surgical navigation and patient outcomes by enabling precise localization and treatment of pathological tissues [8]. Moreover, multimodal MRI systems like BTDNet enhance data representation, reducing ambiguity in diagnostics and supporting targeted drug delivery strategies [9]. Innovations in catheter systems, such as the tendon-driven steerable catheter and active tracking Tiger-shaped catheter, exemplify advancements facilitating precise therapeutic delivery compatible with MRI [3].

Targeted drug delivery systems are pivotal in advancing precision medicine, enabling customized therapeutic interventions tailored to individual molecular and genetic profiles. Advanced methods like engineered exosomes and programmable lipid nanoparticles improve pharmacokinetics, stability, and absorption while minimizing side effects and overcoming drug resistance challenges. By optimizing the administration of synergistic drug combinations and enhancing localization to affected tissues, targeted drug delivery maximizes treatment efficacy and minimizes systemic toxicity, paving the way for more effective and personalized treatment strategies across various diseases, including cancer [10, 6, 11, 12].

1.3 Importance of Molecular Imaging

Molecular imaging is integral to modern medicine, providing insights into biological processes at cellular and molecular levels, thus enhancing diagnostic accuracy and facilitating personalized treatment plans. The use of multiparametric MRI (mpMRI) demonstrates the potential of molecular imaging in visualizing complex biological processes, crucial for tailoring treatment approaches [1]. Accurate tumor characterization is particularly vital in oncology, with voxel-wise analysis of mpMRI data significantly improving glioma grading and patient outcome predictions [13].

In prostate cancer, diffusion-weighted imaging (DWI) has been essential in quantifying non-Gaussian diffusion behaviors in tissues. The introduction of the Apparent Kurtosis Coefficient (AKC) as a clinical evaluation parameter showcases advancements in imaging techniques that molecular imaging facilitates, allowing for nuanced tissue assessments and enhanced diagnostic precision [14]. Additionally, assessing the tumor microenvironment (TME) through optical and magnetic resonance imaging techniques, especially in measuring acidosis and hypoxia, highlights the versatility of molecular imaging in capturing the dynamics of cancerous tissues [15].

Molecular imaging enhances understanding of disease mechanisms and is crucial for advancing personalized medicine. By providing detailed molecular insights, it allows clinicians to customize treatment interventions to individual patient profiles. Innovations like radiomics, which extracts quantitative image features from standard imaging, and multimodal imaging integration facilitate comprehensive disease evaluations and treatment responses. These advancements improve diagnostic accuracy and clinical decision-making efficacy, especially in oncology and complex diseases [16, 17, 18]. Consequently, molecular imaging emerges as a cornerstone of precision medicine, enhancing patient outcomes across diverse medical disciplines.

1.4 Structure of the Survey

This survey provides a comprehensive overview of current advancements and applications of targeted drug delivery systems and molecular imaging technologies, focusing on MRI, PET, image-guided therapy, and theranostics. It begins with an introduction emphasizing the significance of these advanced medical technologies in enhancing diagnostic precision and therapeutic efficacy. Following the introduction, the survey outlines foundational concepts and historical context surrounding non-invasive imaging techniques, highlighting the importance of molecular imaging and radiomics in contemporary diagnostics. Radiomics enhances clinical decision-making by enabling the extraction and analysis of quantitative image features from standard medical imaging, thereby improving diagnostic, prognostic, and predictive accuracy, particularly in cancer research.

The third section focuses on targeted drug delivery, discussing various systems, mechanisms, and recent advancements, especially in nanotechnology and molecular communication, while addressing strategies for overcoming biological barriers to improve drug delivery efficacy. Subsequent sections delve into Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET), examining their principles, applications, and recent technological advancements.

The survey further explores image-guided therapy, highlighting the integration of MRI and PET, the use of robotic-assisted procedures, and image fusion techniques for enhanced therapeutic precision. The principles and applications of molecular imaging are discussed separately, emphasizing its role in cancer therapy and personalized medicine.

Theranostics is examined in detail, covering its concept, integration, and the role of radiomics and nanoplatforms in enhancing its capabilities. The survey concludes with an in-depth discussion on the multifaceted challenges and promising future directions in targeted drug delivery and molecular imaging technologies, critically examining technical limitations such as catheter steerability affecting drug delivery precision and systemic toxicity risks. Additionally, it highlights potential innovations, including advanced drug delivery materials that can enhance pharmacokinetics and stability, and the role of nanorobotics in enabling targeted therapies, underscoring the need for ongoing research to overcome existing barriers and harness these technologies for improved patient outcomes [6, 19, 20].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Non-Invasive Imaging Techniques

Non-invasive imaging techniques have revolutionized diagnostics by providing detailed insights into tissue physiology and pathology without invasive procedures, thereby enhancing the precision and efficacy of medical interventions. Multiparametric MRI (mpMRI) exemplifies this by enabling comprehensive disease composition analysis through various imaging parameters, improving diagnostic accuracy [13]. These techniques are crucial in quantifying intra-tumoral genetic heterogeneity, aiding therapeutic selection and optimizing patient outcomes [21].

Characterizing tissue microstructure through diffusion measurements in muscle and brain tissues underscores the role of non-invasive imaging in elucidating complex biological processes [22]. Techniques such as the fusion of T1-weighted MRI and CFT-PET images enhance Parkinson's disease diagnosis, showcasing the potential of non-invasive imaging to improve diagnostic workflows [23]. Moreover, MRI offers a radiation-free alternative to traditional fluoroscopy-guided interventions, mitigating ionizing radiation concerns [3].

The integration of non-invasive imaging with therapeutic strategies is demonstrated by the Moving Atlas method, which refines diagnostic precision through image registration and tumor growth parameter estimation [24]. The fusion of medical image features with clinical data in CAD systems highlights the importance of integrating diverse data sources for comprehensive diagnostic assessments [25].

Challenges include the heterogeneous nature of the tumor microenvironment (TME) and the need for techniques providing real-time insights into its dynamic properties [15]. Additionally, complexities in enzyme behavior and linking theoretical models to experimental observations complicate the landscape [26]. Non-invasive imaging addresses these challenges by offering real-time, accurate insights into complex biological systems.

Developing benchmarks for classifying brain MRI scans and supporting clinical decisions in breast cancer further illustrates the critical role of non-invasive imaging in diagnostics. However, limitations in deep learning models, which often rely solely on pixel data without incorporating clinical context, highlight the need for ongoing advancements [18]. Non-invasive imaging techniques are integral to modern diagnostics, enhancing therapeutic approaches and improving patient care.

2.2 Molecular Imaging and Radiomics

Molecular imaging and radiomics are pivotal for analyzing medical imaging data, enabling the extraction of quantitative features from standard imaging modalities and enhancing understanding of biological and structural tissue characteristics at the molecular level. This high-throughput approach improves diagnostic, prognostic, and predictive accuracy, particularly in cancer research. By employing advanced image analysis techniques and integrating multiparametric data, radiomics offers valuable insights into tumor heterogeneity and treatment responses, supporting personalized medicine initiatives. However, challenges related to standardization and validation persist, emphasizing the need for rigorous evaluation criteria to ensure the clinical relevance of radiomic findings [17, 27, 13]. Molecular imaging enhances the diagnostic and therapeutic precision of medical interventions, particularly in oncology, where accurate assessment of tumor phenotypes and their microenvironment is vital for effective treatment planning.

Radiomics involves extracting numerous features from medical images using data-characterization algorithms, translating imaging data into high-dimensional mineable data that can enhance clinical decision-making [17]. The integration of radiomics with molecular imaging deepens our understanding of tumor heterogeneity, facilitating the development of personalized treatment strategies by correlating imaging phenotypes with clinical outcomes.

Despite its potential, radiomics faces challenges concerning the robustness and reproducibility of feature extraction across different imaging modalities and institutions. Current methods often rely on a single set of parameters, leading to variability and non-robustness in feature extraction [27]. Addressing these limitations necessitates the development of standardized protocols and advanced computational techniques that can accommodate the heterogeneity of imaging data.

Recent advancements in deep learning have further expanded radiomics' capabilities. By fusing medical images with clinical features, deep learning architectures enhance diagnostic accuracy across various applications, including Alzheimer's disease diagnosis and hepatic microvascular invasion detection [25]. This fusion enables more comprehensive diagnostic assessments, ultimately improving patient outcomes by providing clinicians with detailed insights into disease mechanisms.

3 Targeted Drug Delivery

Category	Feature	Method
Targeted Drug Delivery Systems	Imaging and Analysis	BCa-S[5]
	Predictive Modeling	TC-SR[4]
Mechanisms and Technologies	Precision-Enhancing Techniques	QTRM[28], MMCR[29], DNN-FF[25], GAEM-MC[30], HMSNs@MnO2[31], SP-sLip[32]
	Advanced Imaging Analysis	DRA[33]
Advancements in Nanotechnology	Guidance and Delivery	Min-Gathering[34]
	Control and Manipulation	CGM[35]
	Imaging and Visualization	MFM[36], Fe-NDs[37]
Molecular Communication and Genomic Heterogeneity	Nanoparticle Applications	MMBF-NP[38], ND[39]
Overcoming Biological Barriers	Responsive Delivery Mechanisms	HANs[40], TRMCP[41]
	Acoustic Techniques	UTM[42]
	Machine Learning Approaches	RL-NN[43]

Table 1: This table provides a comprehensive summary of various methods and technologies employed in targeted drug delivery systems. It categorizes the methods into key areas such as targeted drug delivery systems, mechanisms and technologies, advancements in nanotechnology, molecular communication and genomic heterogeneity, and overcoming biological barriers. Each category lists specific features and methodologies, highlighting the diversity and innovation in the field.

The field of targeted drug delivery has gained considerable attention for its potential to enhance therapeutic efficacy while minimizing adverse effects. Table 1 presents a detailed categorization of the methods and technologies that underpin advancements in targeted drug delivery systems, illustrating the breadth of research and development in this critical area of therapeutic innovation. This approach emphasizes the development of systems that deliver drugs specifically to diseased tissues, thereby improving treatment outcomes across various medical conditions. The intricacies of targeted drug delivery systems, including their mechanisms, technologies, and recent advancements, are essential for understanding the innovations shaping contemporary targeted therapies.

3.1 Targeted Drug Delivery Systems

Targeted drug delivery systems have transformed therapeutic strategies by enhancing treatment precision and efficacy through the specific targeting of diseased sites. These systems employ various mechanisms to direct therapeutic agents accurately, minimizing systemic toxicity. Notably, nanoparticle-based delivery systems, including liposomes, polymeric nanoparticles, dendrimers, and mesoporous silica nanoparticles (MSNs), have significantly improved therapeutic efficacy by ensuring that drugs are delivered directly to target tissues [7].

Multifunctional nanoprobes that integrate drug delivery with MRI contrast enhancement exemplify the potential of targeted systems to improve cancer treatment specificity and effectiveness [31]. In breast cancer, the Cancer-Net BCa-S approach utilizes deep radiomics to predict the Scarff-Bloom-Richardson (SBR) grade based on volumetric synthetic correlated diffusion imaging (CDI) data, leveraging deep learning for accurate grading and improved therapeutic decision-making [5]. Similarly, treatment-conditioned regression models have been proposed to align treatment information with MR scans, optimizing therapeutic outcomes [4].

Hydrogels have emerged as versatile platforms for targeted drug delivery, offering unique physical properties and controlled release mechanisms, with recent advancements expanding their applications across therapeutic areas [12]. Hydroxyapatite nanoparticles (HANs) are also gaining attention for their biocompatibility and functionalization capacity, positioning them as promising candidates for targeted therapies [40].

Despite these advancements, challenges such as overcoming the blood-brain barrier (BBB) remain significant. The random orientation of functional plasma proteins in the corona hinders interaction with receptor-binding sites essential for crossing the BBB [32]. Innovative strategies are required to enhance the accessibility and efficacy of targeted drug delivery systems.

The ongoing development of targeted drug delivery systems continues to transform therapeutic interventions, providing personalized and effective treatment options that address the limitations of traditional methods. Innovations in drug design and radiomic analysis are anticipated to play pivotal roles in enhancing precision medicine, improving clinical decision-making, and leading to better patient outcomes, particularly in cancer treatment [17, 6].

3.2 Mechanisms and Technologies

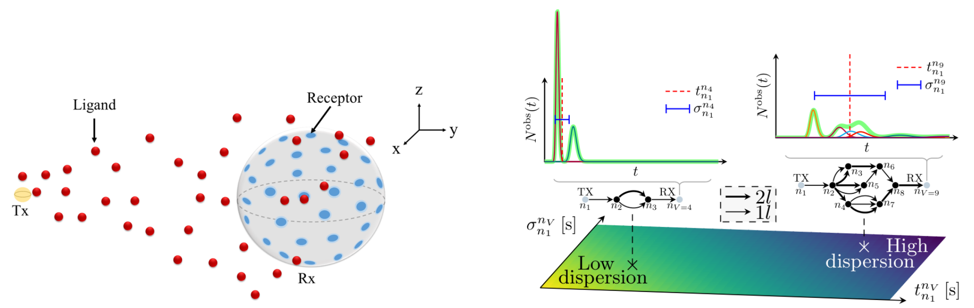
The advancement of targeted drug delivery systems relies on sophisticated mechanisms and technologies that enhance therapeutic precision and efficacy. One primary challenge is the complex dynamics of signaling molecule transport within the branched cardiovascular system, complicating effective communication [38]. Innovative approaches like Localization-Enabled Relay Molecular Communication (LE-RMC) utilize a relay network of Drug Nanoparticles (DgNs) to optimize localization and delivery processes, improving therapeutic outcomes [31].

In programmable lipid nanoparticles (LNPs), achieving effective drug delivery amidst complex biological environments remains challenging. The need for programmable responses to stimuli is critical, enabling LNPs to adapt to dynamic physiological conditions [32]. Bioinspired liposomes (SP-sLip) that modify their surface with peptides derived from A 1-42 have shown potential in enhancing brain-targeted delivery through specific interactions with lipid-binding domains of exchangeable apolipoproteins [25].

Technological advancements include deep learning-based radiomics approaches that address challenges in qualitative imaging evaluations. For instance, transformer-based deep learning methods improve diagnostic accuracy by classifying the primary organ site of brain metastases [33]. The integration of volumetric deep radiomic features from synthetic correlated diffusion imaging (CDIs) has proven effective in predicting the SBR grade of breast cancer, utilizing advanced deep learning techniques to analyze non-invasive imaging data [31].

Cyclic microjetting offers a novel mechanism for enhancing drug delivery precision [44]. MRI-powered magnetic miniature capsules exemplify the integration of imaging technologies with drug delivery, utilizing High-Intensity Focused Ultrasound (HIFU) for precise drug release [29]. However, guiding multiple particles simultaneously in complex biological environments remains a challenge [35].

The continuous evolution of mechanisms and technologies in targeted drug delivery is crucial for advancing precision medicine. By addressing current challenges and incorporating innovative techniques, these advanced therapeutic systems can significantly enhance treatment efficacy for a wide range of medical conditions, including cancer and other complex diseases [18, 6, 19, 11].



(a) Receptor-Ligand Interaction in a Molecular System[28]

(b) Time-Dependent Observation of a Network with High Dispersion and Low Dispersion[30]

Figure 2: Examples of Mechanisms and Technologies

As illustrated in Figure 2, targeted drug delivery represents a cutting-edge approach in medicine aimed at enhancing therapeutic efficacy and specificity. The first example, "Receptor-Ligand Interaction in a Molecular System," highlights the intricate dynamics between receptors and ligands, which are crucial for ensuring that therapeutic agents are directed to specific cellular targets, minimizing off-target effects. The second example, "Time-Dependent Observation of a Network with High Dispersion and Low Dispersion," emphasizes the importance of temporal dynamics in drug delivery systems, illustrating how varying dispersion levels affect drug delivery and efficacy over time. Together, these examples underscore the complexity and potential of targeted drug delivery systems in revolutionizing therapeutic practices [28, 30].

3.3 Advancements in Nanotechnology

Method Name	Technological Innovations	Control Mechanisms	Therapeutic Applications
Fe-NDs[37]	Fe-doped Magnetic	Magnetic Fields	Targeted Therapies
MFM[36]	Magnetic Force Microscopy	Magnetic Fields	Biomedical Applications
CGM[35]	Magnetic Force Microscopy	Acoustic And Magnetic	Cancer Therapy
UTM[42]	Asymmetric Trapping Beam	Acoustic Radiation Force	Drug Delivery Efficacy
Min-Gathering[34]	-	Global External Forces	Targeted Drug Delivery
RL-NN[43]	-	Q-learning	Targeted Therapies

Table 2: Overview of recent technological advancements in nanotechnology, highlighting various methods, their respective innovations, control mechanisms, and therapeutic applications. The table encapsulates the integration of magnetic fields, acoustic forces, and artificial intelligence in enhancing targeted drug delivery and other biomedical applications.

Recent advancements in nanotechnology have significantly enhanced the efficacy and precision of targeted drug delivery systems, addressing longstanding therapeutic delivery challenges. Notable innovations include Fe-doped magnetic nanodiamonds (NDs), which exhibit nearly seven times higher T2 relaxivity than conventional NDs, underscoring the potential of nanotechnology in improving imaging and therapeutic interventions, particularly in cancer therapy [37].

Magnetic Force Microscopy (MFM) for imaging superparamagnetic iron oxide nanoparticles (SPIONs) in liquid environments represents another breakthrough, facilitating precise characterization essential for integrating SPIONs into targeted drug delivery systems [36]. Understanding nanoparticle behavior in biological environments is crucial for optimizing their design and functionality in therapeutic applications.

Innovative approaches like the Collective Guiding Method utilize acoustic and magnetic fields to control self-propelled particle motion, enhancing nanoparticle delivery precision [35]. Simultaneous imaging and manipulation of microbubbles using ultrasonic trapping further illustrate advancements in this field, increasing therapeutic agent concentration at specific locations [42].

AI-generated, for reference only.

The integration of dynamically changing magnetic fields and drag forces enables the creation of stable aggregation points without feedback, which is vital for achieving stable and controlled therapeutic agent delivery [45]. Additionally, global external forces in algorithmic methods optimize particle movement towards target regions, enhancing drug delivery processes [34]. The use of Q-learning for real-time path optimization in nanorobots represents a significant advancement, allowing adaptive responses to environmental changes and improving targeting accuracy [43].

These advancements in nanotechnology are reshaping targeted drug delivery systems, providing innovative solutions that enhance therapeutic outcomes. As research progresses, the integration of sophisticated nanorobotic systems and programmable lipid nanoparticles is expected to significantly enhance precision medicine by enabling targeted drug delivery, improving diagnostic capabilities, and facilitating personalized treatment strategies, ultimately leading to better patient care outcomes. Table 2 provides a comprehensive summary of recent advancements in nanotechnology, showcasing the diverse methods and innovations that are contributing to enhanced targeted drug delivery systems. This evolution is supported by a growing body of literature documenting diverse applications, ranging from single-cell manipulation to advanced imaging techniques that bolster diagnostic accuracy and treatment efficacy [46, 6, 19, 10].

3.4 Molecular Communication and Genomic Heterogeneity

Molecular communication and genomic heterogeneity are pivotal in the efficacy of targeted drug delivery systems, influencing therapeutic agent interactions with biological environments. A significant challenge in molecular communication is the interaction between therapeutic nanoparticles and blood flow within diseased arteries. Integrating mathematical modeling with nanoparticle behavior provides insights into these interactions, optimizing drug delivery strategies [38]. Factors such as receptor saturation and trafficking time can complicate the transport of therapeutic agents, impacting efficacy [47].

Enzyme behavior in molecular communication systems is categorized into active (nonequilibrium) and equilibrium models, contributing to enhanced nanoscale diffusion and chemotaxis. These mechanisms are crucial for designing drug delivery systems that navigate complex biological environments effectively [26]. Magnetic nanoparticles (MNPs) serve as information carriers in molecular communication systems, allowing external magnetic fields to control nanoparticle movement and enhance targeted delivery precision [48].

Genomic heterogeneity introduces complexity into targeted drug delivery, as variations in genetic expression can significantly influence drug response and resistance. Personalized therapeutic approaches that consider individual genetic profiles are essential for optimizing treatment efficacy [49]. Nanodevices capable of controlled release of multiple signaling molecules present a promising avenue for addressing these challenges, enabling precise modulation of therapeutic delivery [39].

Hydrogels, while promising as drug delivery vehicles, face challenges such as hydrophobicity of therapeutic drugs and weak tensile strength, which can lead to premature drug release before reaching target sites [12]. However, innovative approaches using hydroxyapatite nanoparticles for colon cancer treatment demonstrate potential for enhancing therapeutic outcomes by leveraging their unique properties [40].

Exploring molecular communication and genomic heterogeneity is critical for advancing targeted drug delivery systems. By addressing molecular diffusion, receptor interactions, and genetic variability, researchers can enhance targeted therapeutic interventions. These advancements align with precision medicine principles, focusing on tailoring treatments based on individual patient profiles through technologies like molecular profiling and genomic analysis. Improved drug delivery systems, such as programmable lipid nanoparticles, can optimize pharmacokinetics and facilitate precise targeting, overcoming challenges like drug resistance and toxicity. This integrated approach aims to improve treatment efficacy while addressing the unique biological characteristics of tumors and patient-specific factors, ultimately leading to more effective and personalized healthcare solutions [17, 6, 10, 50].

3.5 Overcoming Biological Barriers

Overcoming biological barriers is a formidable challenge in targeted drug delivery systems, particularly due to the restrictive nature of barriers like the blood-brain barrier (BBB) and the complex dynamics within biological environments. These barriers impede drug bioavailability and hinder effective delivery of therapeutic agents to target sites [6]. The nonspecific distribution of chemotherapeutics and their associated severe side effects on healthy tissues complicate the development of effective treatment strategies [7].

Recent advancements have introduced innovative strategies to address these challenges. Hydroxyapatite nanoparticles (HANs) leverage their inherent biocompatibility and bioactivity for controlled drug loading and release in response to acidic tumor microenvironments, enhancing delivery precision [40]. The integration of magnetic nanoparticles (MNPs) in molecular communication systems has been explored, although potential particle adsorption at channel boundaries affects the number of MNPs reaching the target, impacting communication performance [48].

Approaches applying uniform external forces to gather particles in complex environments have shown promise in improving drug delivery precision, facilitating therapeutic agent localization within the body, minimizing side effects, and enhancing treatment efficacy. The combination of advanced imaging and delivery systems, such as simultaneous acoustic trapping and imaging, maintains high microbubble concentrations at targeted locations, effectively overcoming spatial limitations imposed by biological barriers [42].

Reinforcement learning frameworks for nanorobots represent a significant advancement, allowing them to autonomously navigate and detect cancer cells based on biomarker concentration gradients, optimizing therapeutic agent delivery in dynamic biological environments [43]. Modeling molecular communications provides insights into optimizing drug delivery rates by capturing congestion dynamics, crucial for enhancing precision [47].

Despite these advancements, challenges persist in achieving precise optical focusing in deeper tissues, as existing methods are often invasive or limited in efficiency [41]. Additionally, interactions between nanoparticles and blood flow, along with buffering effects in molecular communication models, require further exploration for optimizing drug delivery strategies.

Continuous exploration of innovative strategies to bypass biological barriers is essential for advancing targeted drug delivery systems and enhancing therapeutic efficacy. By addressing complexities posed by biological barriers and improving drug delivery mechanisms, researchers can create more targeted and effective therapeutic interventions aligned with precision medicine principles. Recent advancements, such as programmable lipid nanoparticles and engineered exosomes, enable precise modulation of drug pharmacokinetics, stability, and absorption, improving therapeutic efficacy while minimizing side effects. These innovations facilitate tailored delivery of therapeutics to specific cells or tissues, contributing to successful treatment outcomes for various diseases, including cancer and genetic disorders [6, 11, 10].

Feature	Targeted Drug Delivery Systems	Mechanisms and Technologies	Advancements in Nanotechnology
Delivery Mechanism	Nanoparticle-based Systems	Relay Molecular Communication	Magnetic Nanodiamonds
Technological Innovation	Deep Radiomics	Transformer-based Deep Learning	Q-learning Optimization
Current Challenges	Blood-brain Barrier	Particle Guidance	Nanoparticle Behavior

Table 3: This table provides a comprehensive comparison of different targeted drug delivery systems, mechanisms, and technological advancements in nanotechnology. It highlights the delivery mechanisms, technological innovations, and current challenges associated with each category, offering insights into the diverse approaches and ongoing research in this field. Such comparisons are crucial for understanding the progress and hurdles in enhancing therapeutic precision and efficacy through advanced drug delivery methods.

4 Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) is a pivotal non-invasive medical imaging technology that provides unparalleled insights into the human body. Understanding the foundational principles of MRI elucidates its mechanics and highlights its diverse applications across various medical fields. The following subsection explores MRI's principles and applications, offering a comprehensive overview of its clinical utility.

4.1 Principles and Applications of MRI

MRI is renowned for its exceptional soft-tissue contrast and spatial resolution, crucial for diagnosing a wide range of medical conditions. It operates by aligning hydrogen nuclei within a strong magnetic field, followed by radiofrequency pulses that perturb this alignment. As the nuclei realign, they emit signals that are transformed into detailed images, revealing tissue structure and function [51].

In oncology, MRI plays a vital role in tumor characterization and monitoring therapeutic responses. Techniques like Dynamic Contrast Enhanced MRI (DCE-MRI) evaluate tumor biology, while motion correction techniques ensure accurate liver lesion assessment [52]. Fe-doped magnetic nanodiamonds (Fe-NDs) enhance MRI contrast by improving T2 relaxation times, showcasing their application in imaging [37].

MRI aids in visualizing brain structures for neurological disorders, tackling challenges of reconstructing high-quality images from undersampled data through machine learning techniques [53]. Deep learning methods enhance image quality, resolution, and speed, boosting MRI's clinical utility [54].

Advancements in MRI technology, such as optimizing design parameters through Mutual Information Based Optimal Experimental Design (MI-OED), enhance metabolic exchange rate recovery [55]. Overhauser MRI (OMRI) with nanodiamonds improves contrast by transferring spin polarization to water molecules, enhancing detectability of pathological changes [56].

Despite its strengths, MRI faces challenges like imaging speed and high-quality reconstruction. Continuous time-dependent score functions and numerical SDE solvers address these challenges, ensuring data consistency and improved image quality [57]. Attenuation correction for PET-MRI remains a hurdle due to tissue attenuation imaging limitations [58].

Integrating MRI with therapeutic applications, particularly in image-guided interventions, enhances diagnostic and therapeutic capabilities. Advanced technologies like deep learning and high-field MRI (0.55T and 7T) improve image detail and tissue characterization, facilitating accurate patient management [54, 53]. Generative models for late contrast-enhanced images exemplify MRI's potential in precise localization and treatment of pathological tissues, solidifying MRI's role in precision medicine.

4.2 Advancements in MRI Techniques

Recent advancements in MRI techniques have enhanced diagnostic and therapeutic capabilities, driven by innovations in imaging precision, computational integration, and hardware improvements. Optimizing Nonlinear Inversion (NLINV) methods for multi-GPU systems improves temporal resolution for dynamic imaging applications [59].

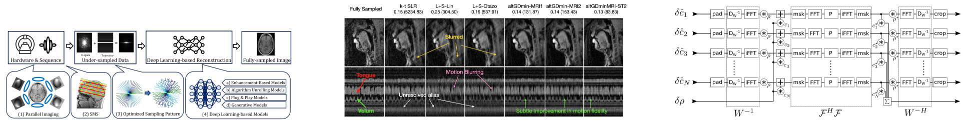
Deep learning models have propelled MRI advancements, particularly in image quality and diagnostic accuracy [54]. Machine learning frameworks categorize research into MRI reconstruction methods, highlighting deep learning's advantages over traditional techniques [53]. A fully convolutional neural network architecture enhances MRI predictions by reducing prediction residuals [58].

Innovations in MRI contrast enhancement, such as Fe-doped magnetic nanodiamonds, exemplify significant advancements, ensuring non-toxicity while improving T2 relaxation times and image contrast [37]. OrCEST imaging improves specificity by subtracting overlapping signals, offering a refined approach compared to conventional methods [56].

Optimizing MRI design parameters, like introducing time-varying flip angles, enhances metabolic exchange rate optimization compared to constant flip angles [55]. Motion correction techniques, such as PCA-based dissimilarity metrics for DCE-MRI, improve dynamic imaging accuracy [52].

The score-based diffusion model demonstrates superior performance in reconstructing MRI images from sub-sampled data, addressing imaging speed and quality challenges [57]. Deep learning algorithms and 0.55T and 7T MRI technologies enhance diagnostic accuracy and therapeutic interventions, offering a safe, non-invasive alternative to traditional imaging methods [54, 53].

As shown in Figure 3, MRI has seen significant advancements in imaging techniques and reconstruction methods. The integration of deep learning into MRI reconstruction enhances image quality, incorporating parallel imaging, spatial modulation spectroscopy (SMS), and optimized sampling patterns. Comparative analysis highlights the effectiveness of techniques like k-t SLR, L+S-Lin, and



(a) Deep Learning-Based MRI Reconstruction: A Comprehensive Approach[60]

(b) Comparison of Different MRI Reconstruction Methods[61]

(c) A Block Diagram of a Signal Processing System[59]

Figure 3: Examples of Advancements in MRI Techniques

altGDmin-MRI variants, focusing on reconstruction quality metrics. The signal processing system block diagram underscores the role of signal processing in MRI, essential for accurate and efficient image reconstruction. These advancements collectively underscore the transformative impact of cutting-edge technologies on MRI, paving the way for more precise and faster diagnostic imaging [60, 61, 59].

4.3 Future Directions in MRI Technology

The future of MRI technology is set to be shaped by advancements in imaging techniques, computational methodologies, and hardware innovations. Super-resolution methods enhance image quality and predictive accuracy, surpassing traditional interpolation techniques and reducing scan times while maintaining high image fidelity [62].

Active sampling methods promise to accelerate MRI scans, with future research focusing on online settings and realistic MRI data applications to enhance clinical efficiency [63]. Hardware innovations, like metasurfaces, enhance signal-to-noise ratio (SNR) and image quality, facilitating higher resolution images in shorter scan times [46].

Sodium MRI, despite challenges, offers insights into cellular processes by differentiating sodium concentrations [64]. Deep learning techniques in MRI reconstruction, exemplified by DeepMRIRec, reduce scan times while maintaining image quality, beneficial in pediatric radiotherapy planning [65].

Deep learning-based multimodal synthesis methods enhance texture retention and synthesis quality, expanding MRI's applicability in diverse clinical scenarios [66]. Integrating 2D object detection with 3D semantic segmentation improves accuracy in tumor localization and tissue differentiation [67].

Key takeaways emphasize deep learning's potential in enhancing MRI reconstruction speed and quality, highlighting the need for robust clinical validation and standardized evaluation metrics [53]. Future research could optimize inference speed, explore score-based approaches in other modalities, and improve model robustness to distribution shifts [57].

Overall, these innovations promise to significantly improve MRI's utility in medicine, enhancing diagnostic precision, reducing scan times, and expanding detectable conditions. As precision medicine progresses, advancements in targeted drug delivery systems and radiomics are anticipated to enhance cancer therapy personalization, optimize treatment efficacy, and improve patient outcomes by addressing pharmacological challenges and refining diagnostic accuracy [17, 6].

In recent years, the integration of artificial intelligence (AI) into medical imaging has revolutionized diagnostic practices, particularly in Positron Emission Tomography (PET). As illustrated in Figure 4, AI plays a pivotal role in advancing PET imaging by enhancing diagnostic accuracy and facilitating cross-modality image synthesis. This figure highlights key areas of improvement, such as the integration of PET with other imaging modalities like MRI and CT, as well as recent technological advancements that bolster image quality and precision. The incorporation of AI techniques not only refines the diagnostic process but also contributes significantly to the development of comprehensive diagnostic frameworks and the pursuit of precision medicine.

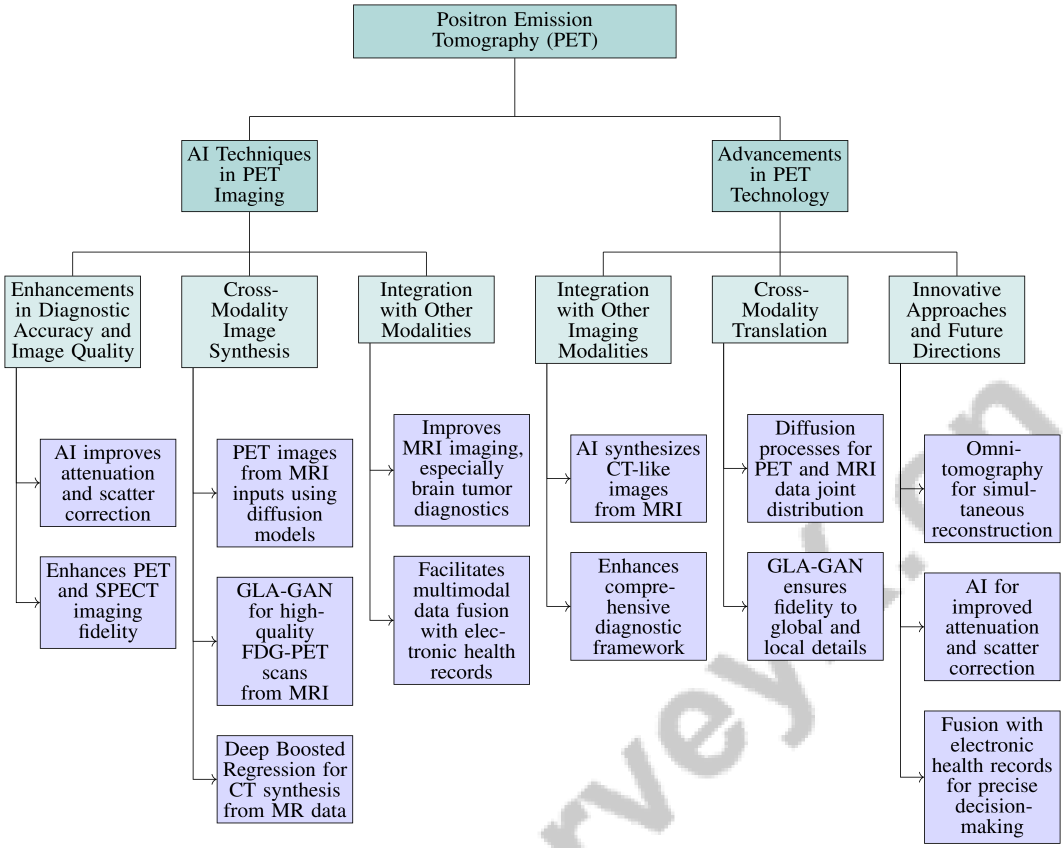


Figure 4: This figure illustrates the role of AI in advancing Positron Emission Tomography (PET) imaging, highlighting key areas such as enhancements in diagnostic accuracy, cross-modality image synthesis, integration with other modalities, and recent technological advancements. AI techniques improve image quality and diagnostic precision, facilitate cross-modality synthesis, and enhance PET's integration with other imaging modalities like MRI and CT, ultimately contributing to comprehensive diagnostic frameworks and precision medicine.

5 Positron Emission Tomography (PET)

5.1 AI Techniques in PET Imaging

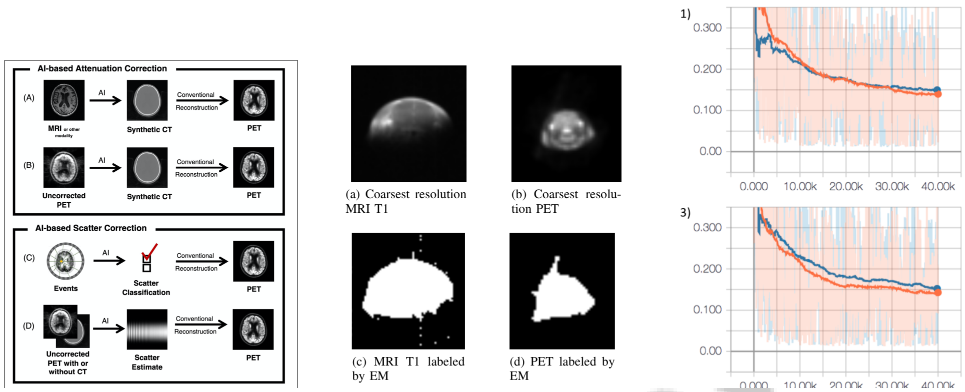
Artificial Intelligence (AI) has significantly enhanced Positron Emission Tomography (PET) imaging by improving diagnostic accuracy and image quality. A key issue in PET imaging is the correction for attenuation and scatter, crucial for generating accurate quantitative images. AI-driven methods have emerged to address these challenges, enhancing the fidelity of PET and single-photon emission computed tomography (SPECT) imaging [68].

AI's potential in cross-modality image synthesis is exemplified by techniques that generate PET images from MRI inputs. Diffusion models using joint probability distributions enable synthetic PET scan synthesis based on MRI data, enhancing diagnostic capabilities [69]. The GLA-GAN method further advances this by producing high-quality FDG-PET scans from MRI data, utilizing both global and local contextual information [70]. Deep learning techniques, such as Deep Boosted Regression, have shown effectiveness in synthesizing CT images from MR data, achieving significant accuracy improvements [58]. While primarily applied to CT synthesis, these principles can enhance PET imaging, particularly in cross-modality translation.

AI integration also shows promise in improving MRI imaging, especially in brain tumor diagnostics, where it significantly boosts diagnostic accuracy [51]. This highlights AI's potential not only to enhance PET imaging but also to improve its synergy with other modalities, providing comprehensive diagnostic insights.

AI-generated, for reference only.

AI's application in PET imaging represents a transformative advancement, elevating diagnostic accuracy and quality. As AI techniques progress, they are poised to play an increasingly crucial role in enhancing PET's clinical utility and advancing precision medicine. Recent innovations have improved attenuation and scatter correction for PET and SPECT, allowing accurate quantitative imaging without a CT scan, enhancing PET-only and SPECT-only scanners' performance, and accelerating image reconstruction, thus increasing patient throughput. Furthermore, integrating AI with electronic health records through deep learning facilitates multimodal data fusion, leading to more precise diagnostics and treatment strategies, especially in complex cases like brain tumors [71, 68, 18, 51].



(a) AI-based Attenuation and Scatter Correction in PET Imaging[68]

(b) MRI and PET images of a brain tumor[72]

(c) Comparison of two models in terms of accuracy over time[58]

Figure 5: Examples of AI Techniques in PET Imaging

As illustrated in Figure 5, PET imaging serves as a powerful diagnostic tool for observing metabolic processes in the body. AI techniques significantly enhance its accuracy and efficiency. The "AI-based Attenuation and Scatter Correction in PET Imaging" example highlights how AI improves image quality by using synthetic CT images generated from MRI or other modalities to correct attenuation and scatter, crucial for accurate PET quantification. MRI and PET images of a brain tumor demonstrate the complementary nature of these modalities in providing detailed anatomical and functional insights. Finally, the comparison of two models' accuracy over time illustrates the dynamic nature of AI model performance in PET imaging, revealing fluctuations in accuracy with iterations and providing insights into model stability and reliability. Collectively, these examples underscore AI's transformative impact on enhancing PET imaging techniques, leading to improved diagnostic capabilities and patient outcomes.

5.2 Advancements in PET Technology

Recent advancements in Positron Emission Tomography (PET) technology have significantly enhanced its capabilities, particularly in integrating with other imaging modalities to improve diagnostic precision and therapeutic planning. AI techniques have been applied to synthesize CT-like images from MRI data, addressing challenges related to attenuation and scatter correction in PET/SPECT imaging. This AI-driven approach not only enhances image quality but also facilitates the integration of PET with other modalities, creating a comprehensive diagnostic framework [68].

The synthesis of PET images from MRI data has been refined using diffusion processes to model the joint distribution of PET and MRI data. This method estimates the joint distribution score, enabling synthetic PET scan generation from MRI inputs, thereby enhancing PET's diagnostic capabilities by leveraging the complementary strengths of both modalities [69]. Such cross-modality synthesis is crucial for improving PET imaging accuracy, especially when PET data is limited or unavailable.

The development of GLA-GAN, an end-to-end generative adversarial network, exemplifies advancements in cross-modality translation by synthesizing PET images from MRI data. This method ensures fidelity to both global structures and local details, producing high-quality FDG-PET scans aligned with the anatomical and functional information provided by MRI [70]. Integrating advanced generative models into PET technology enhances image quality and facilitates seamless PET combination with other modalities, ultimately improving diagnostic accuracy and patient outcomes.

Emerging advancements in PET technology are reshaping its role in medical imaging by enhancing integration with other modalities, such as CT and MRI, through innovative approaches like omni-tomography, which aims for simultaneous reconstruction of multiple imaging techniques. Additionally, incorporating AI for improving attenuation and scatter correction is expanding PET's diagnostic capabilities, enabling accurate imaging without separate CT scans, thus facilitating faster image reconstruction and enhancing patient throughput. The fusion of PET data with electronic health records via deep learning is paving the way for more precise clinical decision-making, ultimately transforming the landscape of diagnostic imaging [68, 17, 16, 18]. As research progresses, these innovations are anticipated to further advance precision medicine, equipping clinicians with comprehensive tools for accurate diagnosis and effective treatment planning.

6 Image-Guided Therapy

6.1 Integration of MRI and PET

The integration of Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) represents a pivotal advancement in image-guided therapy, combining the anatomical precision of MRI with the metabolic insights of PET to enhance diagnostic accuracy and therapeutic planning. MRI provides excellent soft-tissue contrast and spatial resolution critical for anatomical localization, while PET visualizes molecular-level biological processes through radiotracer uptake [51]. This combination is particularly beneficial in oncology for detailed tumor characterization and monitoring therapeutic responses.

AI advancements have further facilitated this integration by enabling cross-modality synthesis and improving image quality. Techniques like diffusion processes model the joint distribution of PET and MRI data, allowing synthetic PET scans from MRI inputs, thus extending diagnostic capabilities [69]. AI methods such as GLA-GAN exemplify this potential by generating high-quality PET images from MRI data, maintaining fidelity to both global structures and local details [70].

Integrating MRI and PET significantly enhances the precision of image-guided interventions, including tumor biopsies and radiotherapy planning, by combining comprehensive anatomical and functional data. Advanced imaging techniques like omni-tomography and multi-tomography facilitate precise localization of pathological tissues and their interactions with surrounding structures, crucial for staging, prognosis, and surgical planning, particularly in complex conditions like breast cancer [67, 16]. This integration supports personalized treatment plans tailored to individual patient characteristics.

The convergence of MRI and PET technologies in image-guided therapy is transformative, providing a comprehensive diagnostic framework that enhances precision medicine. As research progresses, integrating multiple imaging modalities—such as CT, MRI, and PET—through innovative techniques like omni-tomography is expected to significantly improve patient outcomes by enabling comprehensive evaluations of anatomical and physiological conditions across various medical fields, overcoming the limitations of traditional methods [16, 18].

6.2 Robotic-Assisted Procedures and Real-Time Guidance

Robotic-assisted procedures, enhanced by real-time imaging guidance, have revolutionized therapeutic interventions' accuracy and effectiveness. In MRI-guided biopsies for breast cancer, robotic systems precisely target lesions despite breast deformations, while deep learning techniques in pediatric radiotherapy planning reduce MRI scan times without compromising image quality, improving patient experience and diagnostic outcomes. Innovations like CorrSigNet illustrate the potential of integrating robotics and advanced imaging technologies to optimize cancer diagnosis and treatment [65, 73, 74]. The synergy between robotic systems and advanced imaging modalities like MRI and PET facilitates precise localization and treatment of pathological tissues, enhancing outcomes, especially in minimally invasive surgeries where precision is critical.

Combining robotic platforms with real-time imaging modalities allows dynamic procedural adjustments, ensuring optimal intervention strategies. Robotic systems paired with MRI provide high-resolution anatomical images that enhance navigation and manipulation of surgical instruments [51], vital in complex surgical environments like neurosurgery and oncology, where accurate targeting of lesions is essential.

Real-time guidance is crucial for improving therapeutic interventions' accuracy. Techniques like High-Intensity Focused Ultrasound (HIFU) use real-time imaging to monitor therapeutic energy delivery, ensuring targeted treatment of pathological tissues while sparing adjacent healthy structures [29]. Integrating real-time imaging with robotic-assisted procedures reduces intraoperative errors and enhances surgical interventions' safety and efficacy.

Recent machine learning and AI advancements have significantly enhanced robotic-assisted procedures, improving diagnostic accuracy and procedural efficiency. Models like CorrSigNet correlate MRI features with histopathology, achieving high sensitivity and specificity in prostate cancer localization. Multimodal neural networks have demonstrated remarkable accuracy in brain tumor detection, while machine learning techniques in MRI image reconstruction optimize data acquisition and image quality. AI in nanorobot navigation for targeted cancer therapy showcases the potential for more precise treatment strategies, underscoring the transformative impact of these technologies in medical applications [43, 67, 73, 51, 53]. AI-driven algorithms can analyze imaging data in real-time, offering critical insights and decision support during procedures. Integrating AI with robotic systems and real-time imaging holds significant promise for further enhancing precision and outcomes in therapeutic interventions.

The synergy between robotic-assisted procedures and real-time imaging guidance represents a substantial advancement in precision medicine. By improving therapeutic interventions' accuracy and efficacy, these technologies offer promising avenues for enhancing patient outcomes across diverse medical disciplines. As research and technology advance, the fusion of robotics with advanced imaging techniques, such as MRI pulse sequence integration and deep learning-based segmentation, is expected to significantly improve surgical precision and therapeutic effectiveness. This integration facilitates accurate localization and segmentation of tumors and surrounding tissues, enhancing diagnostic models' robustness and supporting better surgical planning and patient outcomes in complex medical scenarios [67, 75].

6.3 Image Fusion Techniques

Medical image fusion techniques are crucial for enhancing diagnostic capabilities by integrating information from multiple imaging modalities to create composite images. This approach harnesses the strengths of different modalities, such as MRI's high spatial resolution and PET's functional insights, to provide a comprehensive view of tissues' anatomical and physiological status [76]. Fusing data from diverse modalities improves guidance in therapeutic interventions, enabling precise localization and targeting of pathological tissues.

In image-guided therapy, image fusion techniques facilitate the seamless integration of anatomical and functional data, vital for accurate diagnosis and treatment planning. Combining MRI's high-resolution anatomical details with PET's functional metabolic data offers a powerful diagnostic tool, allowing clinicians to define tumor boundaries more accurately, assess treatment efficacy, and optimize radiotherapy planning. This multimodal approach enhances clinical decision-making by providing a comprehensive understanding of tumor characteristics and patient responses, ultimately leading to improved patient outcomes in oncology [13, 18, 16, 17, 72]. This integrated approach not only enhances diagnostic accuracy but also supports personalized treatment strategies tailored to individual patient characteristics.

Technological advancements in image fusion have been significantly driven by sophisticated algorithms capable of effectively integrating data from various imaging modalities, including MRI, CT, and PET, along with clinical information. These algorithms employ techniques such as early fusion, where features from different sources are concatenated, and advanced methods like parameter-adaptive pulse-coupled neural networks, which enhance the fusion process by preserving energy and extracting details from images. Recent studies demonstrate that these innovative approaches improve diagnostic accuracy and enhance the visual quality and objective assessment of fused images, making them invaluable in clinical applications such as disease diagnosis and treatment planning [18, 76, 25]. Techniques like wavelet transforms, principal component analysis (PCA), and deep learning-based methods are employed to synthesize high-quality composite images. Applying these advanced fusion techniques ensures that the resulting images retain critical information from each modality, enhancing overall diagnostic and therapeutic utility.

Image fusion techniques have made significant strides in medical imaging, enabling the integration of diverse imaging modalities to provide clinicians with a holistic view of patient conditions. This advancement enhances diagnostic accuracy and therapeutic efficacy by allowing for improved feature extraction and analysis, as evidenced by various studies utilizing deep learning and sophisticated algorithms like nonsubsampled shearlet transform and parameter-adaptive pulse-coupled neural networks. Consequently, clinicians can make more informed decisions, ultimately leading to better patient outcomes in disease diagnosis and treatment planning [18, 76]. As research continues to evolve, integrating cutting-edge fusion techniques is expected to play an increasingly critical role in advancing precision medicine and improving patient outcomes across various medical disciplines.

7 Molecular Imaging

7.1 Principles of Molecular Imaging

Molecular imaging represents a significant leap in medical diagnostics by allowing visualization and quantification of biological processes at cellular and molecular levels within living organisms. This field employs modalities like MRI, PET, and advanced optical techniques to evaluate crucial factors such as acidosis and hypoxia in the tumor microenvironment. By integrating these imaging methods, known as omni-tomography, it achieves high spatial and temporal resolution, enabling detailed mapping of tumor heterogeneity and assessment of therapeutic responses [15, 17, 16]. This integration enhances diagnostic precision and therapeutic planning by detecting molecular and cellular changes prior to anatomical alterations, thus offering earlier diagnosis compared to traditional methods.

Radiomics, a vital component of molecular imaging, extracts quantitative features from medical images using data-characterization algorithms, significantly advancing oncology by correlating imaging phenotypes with clinical outcomes, thus improving diagnostic and prognostic capabilities [17]. This enhances understanding of tumor heterogeneity and supports the development of personalized treatment strategies, aligning with precision medicine goals.

Molecular imaging modalities such as PET and MRI are crucial for insights into metabolic and functional processes. PET visualizes metabolic activity using radiolabeled tracers, while MRI provides high-resolution anatomical images. Their integration with advanced molecular imaging techniques enables comprehensive disease evaluation, enhancing early detection and monitoring of treatment responses. This multimodal strategy leverages sophisticated radiomic analysis to improve diagnostic, prognostic, and predictive accuracy in clinical decision-making [17, 16]. By encompassing morphologic details, physiological functions, and treatment effects, molecular imaging significantly advances personalized medicine and cancer research [18, 46, 27].

7.2 Molecular Imaging in Cancer Therapy

Molecular imaging is pivotal in cancer therapy, enhancing treatment planning and monitoring by visualizing and quantifying biological processes at the molecular level. It provides insights into tumor biology, heterogeneity, and the tumor microenvironment (TME), informing therapeutic decisions. The integration of advanced imaging modalities like PET and MRI with molecular imaging techniques allows for detailed assessment of metabolic and functional tumor characteristics, facilitating early detection and accurate staging [17].

In oncology, molecular imaging is crucial for evaluating targeted therapies' efficacy, enabling real-time monitoring of tumor responses to treatment. This capability is essential for assessing dynamic changes within the TME, such as acidosis and hypoxia alterations, which are critical for understanding therapeutic resistance and efficacy [15]. By elucidating these factors, molecular imaging aids in optimizing treatment regimens, ensuring interventions align with individual tumor characteristics.

Molecular imaging guides precision medicine approaches, exemplified by voxel-wise analysis of multiparametric MRI (mpMRI) data, which improves glioma phenotypes classification, enhancing tumor grading and prognostication [13]. This detailed characterization facilitates developing personalized treatment strategies that align with each patient's cancer's unique molecular and cellular profiles.

Advancements in molecular imaging, particularly through radiomics, have enabled innovative imaging biomarkers that enhance prognostic accuracy and inform therapeutic decision-making. High-throughput quantitative analysis of medical imaging data allows for extracting image-based signatures reflecting tumor characteristics, aiding in personalized cancer management. For instance, mpMRI techniques can predict critical clinical outcomes, such as tumor grade and overall survival, reducing the need for invasive biopsies. This evolution underscores radiomics' potential to transform clinical decision support systems and improve patient care in oncology [17, 13]. These biomarkers provide insights into tumor aggressiveness and potential treatment responses, enhancing cancer therapy planning precision.

Molecular imaging plays a critical role in advancing cancer therapy by offering comprehensive insights into tumor biology and treatment responses. It integrates diagnostic and therapeutic functions, significantly improving treatment planning precision and bolstering personalized medicine approaches. Employing cutting-edge technologies like omni-tomography and radiomics, molecular imaging tailors cancer treatments to individual patient profiles, aiding in accurately assessing tumor characteristics and therapy responses, ultimately improving oncology patient outcomes [15, 17, 16].

7.3 Role in Personalized Medicine

Molecular imaging is crucial in advancing personalized medicine by enabling precise tailoring of treatments based on individual patients' unique molecular and cellular profiles. This approach leverages advanced imaging modalities like PET and MRI to provide insights into the biological processes underlying disease states, facilitating the development of personalized treatment strategies [17]. Integrating molecular imaging with radiomics allows for extracting quantitative imaging features that correlate with clinical outcomes, enhancing understanding of tumor heterogeneity and informing therapeutic decisions [17].

In oncology, molecular imaging characterizes tumor phenotypes and the TME, critical determinants of therapeutic response and resistance [15]. By providing real-time insights into dynamic microenvironmental factors like acidosis and hypoxia, molecular imaging supports optimizing treatment regimens, ensuring interventions are tailored to specific cancer characteristics [15]. This capability is exemplified by voxel-wise analysis of mpMRI data, which significantly improves tumor grading and prognostication [13].

Moreover, molecular imaging facilitates identifying novel imaging biomarkers that provide valuable prognostic information and guide therapeutic decision-making. Derived from quantitative imaging features, these biomarkers offer insights into tumor aggressiveness and potential treatment responses, enhancing cancer therapy planning precision [17]. By integrating diagnostic and therapeutic functions, molecular imaging enhances treatment planning accuracy and supports personalized medicine development, ultimately improving patient outcomes across various medical disciplines.

Molecular imaging serves as a fundamental pillar of personalized medicine by providing in-depth insights into disease mechanisms, facilitating the customization of therapeutic strategies to meet individual patients' unique needs. This approach is bolstered by radiomics, which extracts and analyzes quantitative features from standard medical imaging to improve diagnostic, prognostic, and predictive accuracy in clinical decision-making. Furthermore, advancements in multi-modality imaging, such as omni-tomography, aim to integrate various imaging techniques for a comprehensive understanding of disease processes, ultimately supporting more effective and tailored interventions in patient care [16, 17]. Continued research in advanced molecular imaging techniques is expected to further advance precision medicine, equipping clinicians with the tools necessary to deliver more effective and personalized care.

8 Theranostics

Theranostics has emerged as a transformative approach in personalized medicine by combining diagnostic and therapeutic strategies. This approach enhances treatment precision through advanced drug delivery systems that optimize pharmacokinetics and enable synergistic drug combinations. Real-time monitoring of therapeutic responses is facilitated by integrating medical imaging and electronic health records, allowing dynamic adjustments to patient care based on individual responses and disease progression [45, 18, 6, 73, 19]. The core of theranostics lies in the synergy between diagnostic imaging, therapeutic interventions, and molecular disease characteristics, making it pivotal for advancing personalized treatment strategies in clinical practice.

8.1 Concept and Integration of Theranostics

Theranostics integrates diagnostic and therapeutic functions, facilitating personalized treatment strategies tailored to patients' molecular profiles. This dual functionality is realized through advanced imaging modalities and therapeutic agents targeting specific biomarkers, allowing precise diagnosis and real-time monitoring of therapeutic efficacy [17]. Particularly in oncology, theranostics addresses tumor heterogeneity and the tumor microenvironment (TME), which are critical for effective treatment planning [15].

Clinically, theranostics integrates molecular imaging techniques like PET and MRI to visualize biological processes at cellular and molecular levels. These modalities offer insights into metabolic activity, receptor expression, and microenvironmental factors, essential for accurate disease characterization. By combining diagnostic capabilities with targeted therapies, theranostics enables real-time treatment response assessment and regimen adjustments, ensuring optimal patient outcomes [17].

A key aspect of theranostics is developing multifunctional nanoplatforms that fulfill both diagnostic and therapeutic roles. These platforms deliver therapeutic agents directly to diseased tissues while offering imaging contrast, enhancing treatment specificity and efficacy. Such systems enable seamless transitions from diagnosis to therapy, allowing for precise and personalized interventions [31].

Theranostics represents a pivotal advancement in precision medicine by combining targeted drug delivery with advanced imaging techniques, enhancing diagnostic accuracy and treatment efficacy. This comprehensive approach uses molecular profiling and radiomic analysis to tailor interventions, addressing challenges like drug resistance and toxicity while optimizing pharmacological parameters. Theranostics not only improves clinical decision-making but also has the potential to revolutionize cancer therapy through personalized treatment strategies [17, 6]. As research progresses, theranostics is expected to play an increasingly vital role in enhancing patient care across various medical fields.

8.2 Role of Radiomics in Theranostics

Radiomics is fundamental to theranostics, enhancing personalized treatment by extracting and analyzing quantitative features from medical images. This approach allows detailed tumor phenotype and TME characterization, essential for tailoring therapeutic interventions to the specific molecular and cellular profiles of patients [17]. By correlating imaging phenotypes with clinical outcomes, radiomics provides insights into tumor heterogeneity, enabling the development of personalized treatment strategies aligned with precision medicine principles.

The integration of radiomics into theranostics aids in identifying novel imaging biomarkers that offer prognostic information and guide therapeutic decision-making. These biomarkers, derived from quantitative imaging features, reveal insights into tumor aggressiveness and potential treatment responses, enhancing the precision of cancer therapy planning [17]. This capability is particularly valuable in theranostics, where the seamless integration of diagnostic and therapeutic functions is crucial for real-time monitoring and adjustment of treatment regimens.

Radiomics optimizes treatment strategies by providing insights into dynamic changes within the TME, such as alterations in acidosis and hypoxia, which are critical determinants of therapeutic resistance and efficacy [15]. By enabling real-time assessments of these microenvironmental factors, radiomics strengthens theranostic approaches to deliver targeted therapies tailored to each patient's cancer characteristics.

The role of radiomics in theranostics is essential for advancing personalized medicine. It enhances theranostic approaches by offering insights into disease mechanisms and enabling the customization of therapeutic interventions. The high-throughput analysis of quantitative image features improves diagnostic, prognostic, and predictive accuracy, thereby enhancing patient outcomes across various medical disciplines. Advanced techniques like tensor radiomics and spatial-and-context aware (SpACe) mapping facilitate the development of precise biomarkers and treatment strategies, leading to more effective personalized medicine in cancer care and beyond [17, 8, 27]. As research evolves, integrating advanced radiomics techniques is expected to further enhance theranostics capabilities in precision medicine.

8.3 Nanoplatforms and Hydrogels in Theranostics

Nanoplatforms and hydrogels have become crucial components of theranostics, offering innovative solutions for improved delivery and efficacy of therapeutic agents. These advanced materials integrate diagnostic and therapeutic functions, enhancing the precision and effectiveness of medical interventions. Multifunctional nanoparticles exemplify nanoplatforms, delivering therapeutic agents directly to target tissues while providing imaging contrast, facilitating real-time treatment efficacy monitoring, and enabling dynamic therapeutic regimen adjustments [31].

Manganese dioxide (MnO2)-based nanoplatforms, for instance, enable targeted and controlled drug release, enhancing the therapeutic index of anticancer drugs by specifically targeting cancer cells and improving treatment specificity and effectiveness [31]. Incorporating imaging agents into these nanoplatforms allows simultaneous visualization of biological processes, providing valuable insights into the TME and supporting treatment strategy optimization.

Hydrogels, characterized by unique physical properties and controlled release mechanisms, have gained prominence in theranostics. These polymeric materials provide a versatile platform for delivering therapeutic agents, enabling sustained and localized drug release in response to specific physiological stimuli. Recent advancements in hydrogel technology have broadened their applications across various therapeutic areas, highlighting their potential to enhance drug delivery precision and efficacy [12]. By creating a controlled environment for drug release, hydrogels help reduce systemic toxicity and improve targeted intervention outcomes.

Integrating nanoplatforms and hydrogels into theranostic approaches represents a significant advancement in precision medicine. By enhancing the delivery and efficacy of therapeutic agents, these materials offer promising avenues for improving patient outcomes across a range of medical conditions. As research in programmable lipid nanoparticles and hydrogels progresses, developing innovative nanoplatforms and hydrogel systems is expected to significantly enhance theranostic capabilities. These technologies promise to equip clinicians with sophisticated tools for targeted drug delivery, addressing complex diseases like cancer and genetic disorders while minimizing systemic toxicity and improving patient outcomes. The integration of programmable lipid nanoparticles, which allow for precise spatiotemporal control, along with the tunable properties of hydrogels that facilitate controlled drug release, will enable more effective and personalized therapeutic strategies tailored to individual patient needs [12, 10].

9 Challenges and Future Directions

Advancements in medical technologies require addressing multifaceted challenges in imaging and drug delivery systems, including technical limitations, integration, standardization, biocompatibility, and ethical considerations. Understanding these complexities is crucial for enhancing the efficacy and applicability of these technologies in clinical settings. The following subsections explore these challenges and highlight areas for focused research and innovation.

9.1 Technical Limitations in Imaging and Drug Delivery

Current imaging and drug delivery technologies face technical limitations that impact their efficacy and clinical applicability. In MRI, contamination of CEST signals from overlapping spectra complicates concentration measurements, affecting imaging reliability [56]. Dataset imbalances and the need for validation across diverse clinical settings further challenge the robustness and generalizability of imaging technologies [51]. Signal inconsistencies across modalities often lead to registration failures, compromising data analysis [77]. Additionally, the practical realization of inserting transmembrane proteins into nanodevices limits nanoscale transmitter applications in molecular communication systems [39]. Brownian motion and fluid flow complicate reliable communication in molecular systems, impacting targeted drug delivery precision [48].

In drug delivery, chemotherapy methods often lack specificity, resulting in adverse side effects and limited effectiveness, highlighting the need for targeted approaches [40]. Moreover, current algorithms struggle to process large datasets in real-time, creating bottlenecks in utilizing EHRs for personalized medicine. Addressing these technical limitations is crucial for enhancing imaging and drug delivery technologies, ultimately leading to better patient outcomes through tailored treatments and precise disease detection [46, 6, 20, 17, 25].

9.2 Integration and Standardization Challenges

Integrating and standardizing imaging and therapeutic modalities is a significant challenge in advancing precision medicine. Harmonizing diverse imaging techniques like MRI and PET is difficult due to distinct operational principles and data outputs, leading to inconsistencies in image registration and analysis [16]. Current methodologies often fail to adapt to dynamic clinical environments, resulting in inefficiencies and resource wastage. Robust frameworks are needed to facilitate multimodal imaging data integration, ensuring consistency and reliability across platforms. Standardization efforts should prioritize unified protocols and data formats, enabling seamless communication between systems and integrating multimodal data such as medical imaging and EHRs. Implementing standardized practices is crucial for leveraging advanced technologies like deep learning and radiomics, enhancing clinical decision-making and patient outcomes [18, 16, 2, 62, 17].

9.3 Biocompatibility and Ethical Concerns

The advancement of medical technologies, particularly in targeted drug delivery and molecular imaging, raises biocompatibility and ethical challenges. Long-term biocompatibility of nanomaterials used in drug delivery systems and imaging agents remains inadequately understood, with challenges in scalability and comprehensive evaluation of long-term impacts on human health [19]. Integrating nanotechnology in medicine raises ethical concerns regarding patient consent, privacy, and potential unintended consequences. Rigorous regulatory frameworks are needed to ensure ethical justification and informed patient consent. The scalability of these technologies poses additional challenges, requiring substantial resources and infrastructure for transition from experimental to clinical settings [19]. Ethical considerations also extend to equitable distribution of advanced medical technologies, ensuring all patients access the benefits of precision medicine. Thorough assessments of personalized treatment implications on healthcare costs are crucial to avoid reinforcing existing healthcare disparities [18, 6]. Addressing biocompatibility and ethical concerns is essential for the responsible development and implementation of advanced medical technologies, ultimately leading to improved patient outcomes in precision medicine and diagnostics [18, 46, 6, 20, 19].

9.4 Innovations in Molecular Imaging and Theranostics

Innovations in molecular imaging and theranostics are poised to enhance precision medicine by addressing challenges and expanding diagnostic and therapeutic capabilities. Multifunctional nanoparticles and advanced imaging-guided drug delivery systems aim to improve treatment precision by integrating therapeutic and diagnostic functions, effectively targeting diseased tissues [7]. The exploration of orCEST parameters for various conditions represents a promising frontier in molecular imaging, offering enhanced diagnostic insights into complex diseases [56]. AI integration into molecular imaging is expected to drive advancements, focusing on generative adversarial networks for data availability and adaptive sampling techniques [58]. Refining groupwise registration methods to improve robustness against motion artifacts across different imaging modalities will enhance image quality and diagnostic accuracy [52].

In theranostics, novel delivery systems that combine multiple therapies are essential for overcoming drug resistance and enhancing therapeutic efficacy. Future research may explore dimensional aggregation methods in various biological contexts, including using vesicles or saline solutions to enhance particle mobility and targeting [45]. Theoretical analysis of magnetic nanoparticle-based molecular communication systems provides a foundation for future experimental work, emphasizing optimizing magnetic field configurations and exploring different microfluidic geometries [48]. Future studies should concentrate on in vivo validation of hydroxyapatite nanoparticles and explore modifications to enhance therapeutic efficacy [40]. The proposed nanoscale transmitter design is suitable for health monitoring and targeted drug delivery applications, highlighting potential innovative solutions in theranostics [39].

These innovations in molecular imaging and theranostics hold potential to advance precision medicine by improving the precision and efficacy of diagnostics and therapeutics. As research evolves, these advancements are expected to play a crucial role in addressing current challenges and enhancing patient outcomes. Future research should focus on enhancing algorithm robustness against diverse data types and exploring real-time applications across different domains [78]. Developing shared terminology and metrics for multimodal fusion, as well as utilizing comprehensive clinical data to improve model performance in medical imaging tasks, will be essential for maximizing the impact of these innovations [18].

10 Conclusion

The survey underscores the pivotal advancements in targeted drug delivery and molecular imaging technologies, highlighting their profound influence on enhancing diagnostic and therapeutic paradigms in modern medicine. The synergy between these technologies facilitates the development of tailored treatment approaches, significantly enhancing patient care across diverse medical domains. Techniques like multiparametric MRI (mpMRI) have substantially improved the precision of oncological diagnoses by refining tumor characterization processes. In parallel, molecular imaging techniques, including diffusion-weighted imaging, have proven invaluable in clinical assessments, particularly through the analysis of non-Gaussian diffusion patterns.

The role of nanotechnology, exemplified by programmable lipid nanoparticles, is crucial in the evolution of drug delivery systems, despite the complexities inherent in their design and the regulatory landscape. The versatility of hydrogels in delivering therapeutic agents further exemplifies their potential in augmenting treatment efficacy for various conditions. Furthermore, the integration of artificial intelligence in imaging has markedly enhanced diagnostic accuracy, as demonstrated by the successful classification of brain tumors using multimodal AI approaches. The evaluation of clinical decision indices in breast cancer has revealed intrinsic biases, indicating the necessity for continuous refinement of clinical decision support systems.

The progression of targeted drug delivery and molecular imaging technologies is integral to the advancement of precision medicine. By addressing current challenges and capitalizing on these technological innovations, there is potential to significantly elevate the precision and effectiveness of medical diagnostics and therapeutics, thereby enhancing patient outcomes. The potential application of nanorobots in refining targeted therapies and mitigating adverse effects further emphasizes the transformative impact of these innovations in medical treatment. Continued research and integration of these technologies are essential for advancing medical science and achieving more effective, personalized healthcare solutions.

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