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A Critical Review on Therapeutic Imaging in Oncology

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Abstract. Oncology, a critical discipline within medical science, is dedicated to understanding the mechanisms of tumor development, progression, diagnosis, and treatment. As medical technologies advance, cancer therapies have diversified to include surgical resection, radiotherapy, chemotherapy, and more recently, immunotherapy. However, challenges persist—particularly in accurately locating tumor tissues, monitoring treatment efficacy in real time, and minimizing treatment-related side effects. Therapeutic imaging technologies have emerged as essential tools to address these challenges, enhancing the precision and adaptability of oncological care. By providing detailed visualization of tumor structure and function, these technologies support accurate diagnosis, guide therapeutic interventions, and enable dynamic treatment evaluation. Recent innovations—such as multimodal imaging, artificial intelligence-driven diagnostics, and molecular-targeted approaches—have significantly expanded the capabilities of therapeutic imaging. Technologies like dynamic full-field optical coherence tomography (D-FFOCT), microscopic optical tomography (MOST/fMOST), and near-infrared fluorescent probes demonstrate the growing role of intelligent imaging in surgical navigation, pathology mapping, and phototherapy. Meanwhile, the integration of modalities such as photoacoustic imaging, MRI, and PET improves early-stage tumor detection and therapeutic monitoring. Emerging strategies, including nanoparticle self-assembly and multifunctional molecular probes, are advancing the convergence of diagnostics and therapy. This review aims to provide a comprehensive overview of therapeutic imaging in oncology, examining its theoretical foundations, clinical applications, and future development trends.

Keywords: Therapeutic Imaging, Oncology, Multimodal Imaging

1. Introduction

Oncology, as a crucial branch of medical science, focuses on the study of tumor occurrence, progression, diagnosis, and therapeutic strategies. With the rapid advancement of medical technology, treatment modalities for cancer have significantly diversified, encompassing surgical resection, radiotherapy, chemotherapy, and the emerging field of immunotherapy. Despite these advances, clinicians continue to face considerable challenges, such as accurately locating tumor tissues, real-time monitoring of therapeutic efficacy, and mitigating treatment-related side effects. Consequently, therapeutic imaging technologies have emerged as essential tools within oncology, offering promising solutions to these persistent clinical issues.

Therapeutic imaging technology enhances the precision of cancer diagnosis and treatment by facilitating accurate tumor localization, enabling real-time assessment of treatment responses, and allowing adaptive modifications to therapeutic regimens [1]. With ongoing technological innovations and interdisciplinary integration, therapeutic imaging is expected to play an increasingly pivotal role in oncology, profoundly impacting future clinical practices.

Recent developments in tumor therapeutic imaging have witnessed significant breakthroughs, particularly in multimodal imaging, intelligent diagnostics, and precision therapeutics. Dynamic full-field optical coherence tomography (D-FFOCT), combined with artificial intelligence (AI), enables rapid and precise intraoperative delineation of breast cancer margins [2]. Furthermore, microscopic optical tomography (MOST/fMOST) techniques are advancing the construction of detailed tumor pathology maps, thereby guiding targeted nano-drug delivery. Near-infrared fluorescent probes have demonstrated efficacy in tumor vascular imaging and phototherapy applications.

Multimodal fusion imaging, integrating technologies such as photoacoustic imaging, magnetic resonance imaging (MRI), and positron emission tomography (PET), significantly improve diagnostic sensitivity and treatment monitoring, especially in early-stage tumors [3]. For instance, photoacoustic imaging provides high-resolution visualization of superficial tumor structures. Concurrently, innovative strategies, such as nanoparticle self-assembly technologies, are being developed to amplify imaging signals, while multifunctional molecular probes offer combined diagnostic and therapeutic functionalities, thus enhancing the convergence of tumor diagnosis and therapy.

In the Chinese research context, emphasis has been placed on addressing clinical necessities, overcoming limitations inherent in traditional imaging techniques, and fostering multidisciplinary collaborations [1][4]. These efforts are crucial in translating novel imaging technologies into clinical practice, thereby providing advanced tools for more precise and effective cancer diagnosis and treatment. This study provides a detailed review of the therapeutic imaging from theory, application and development perspectives.

2. The basic theory of therapeutic imaging

2.1. The basic principles of imaging technology

The fundamental principle of imaging technology lies in the interaction between various physical signals—such as light, sound waves, and electromagnetic waves—and matter, with images produced through the detection and processing of these signals. In the medical field, commonly employed imaging modalities include X-ray imaging, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound imaging, positron emission tomography (PET), and photoacoustic imaging.

Recent advancements in these technologies have greatly accelerated the progress of molecular imaging, thereby transforming diagnostic and therapeutic approaches in clinical medicine [1]. Molecular imaging utilizes two- and three-dimensional imaging techniques to visualize and distinguish physiological and pathological processes at the cellular and even subcellular levels in vivo [1]. This approach allows for both qualitative and quantitative analyses, offering highly sensitive detection capabilities that facilitate early disease diagnosis.

2.2. The core goal of therapeutic imaging

Therapeutic imaging offers patients more precise, efficient, and safer treatment options by enabling accurate diagnosis, guiding therapeutic interventions, and evaluating treatment efficacy. High-resolution imaging modalities—such as computed tomography (CT) and magnetic resonance imaging (MRI)—allow for the clear visualization of tumor location, size, morphology, and spatial relationships with surrounding tissues. This facilitates the accurate identification of lesions and the early detection of tumors, enabling timely clinical intervention and improving both cure rates and patient survival outcomes.

Moreover, imaging technologies provide valuable prognostic information. By assessing features such as tumor vascularization, metabolic activity, and other physiological characteristics, clinicians can estimate tumor malignancy and better evaluate the patient’s risk profile, thereby informing personalized treatment planning and prognosis prediction.

3. Application of therapeutic imaging in tumor treatment

3.1. Application of therapeutic imaging in radiotherapy

Several advanced magnetic resonance imaging (MRI) techniques, though not yet widely adopted in routine clinical practice—have been investigated to address the limitations of conventional MRI in evaluating rectal cancer during initial staging and post-treatment restaging [3]. Notable among these are dynamic contrast-enhanced MRI (DCE-MRI), magnetization transfer ratio (MTR), and textural analysis approaches such as radiomics. For lymph node assessment, emerging strategies including novel contrast agents and PET/MRI integration have shown potential in enhancing the accuracy of nodal status evaluation. Furthermore, these advanced techniques have been explored as imaging biomarkers for predicting clinical outcomes, offering promising avenues for personalized treatment planning and prognostication

3.2. Advanced imaging-guided technologies in interventional oncology and phototherapy

Therapeutic imaging technologies play a pivotal role in interventional treatments, particularly in tumor ablation procedures such as radiofrequency ablation (RFA) and microwave ablation (MWA). Imaging modalities including ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI) enable precise tumor localization and real-time guidance of treatment instruments [3]. Real-time ultrasound is radiation-free and well-suited for procedures involving the liver, kidneys, and other abdominal organs. CT offers high spatial resolution, making it ideal for interventions in the lungs, bones, and other complex anatomical regions. MRI provides superior soft tissue contrast but requires more specialized equipment and operational conditions.

Multimodal image fusion—such as PET-CT—enhances localization accuracy by integrating the strengths of different imaging modalities. Advanced techniques including three-dimensional (3D) reconstruction and AI assistance can optimize needle trajectories and automatically delineate tumor boundaries. Navigation systems enable real-time tracking of interventional instruments, improving procedural precision.

Intraoperative evaluation of ablation efficacy can be performed using contrast-enhanced ultrasound, enhanced CT or MRI, or temperature mapping via MRI. To address respiratory-induced tumor motion, techniques such as respiratory gating or marker tracking are employed. In anatomically complex regions, robotic assistance can further enhance procedural accuracy.

Nuclear magnetic resonance imaging (NMRI), commonly referred to as magnetic resonance imaging (MRI), operates by detecting electromagnetic signals emitted by atomic nuclei within an external gradient magnetic field [4]. This allows for the determination of the position and type of nuclei within a given material and facilitates the reconstruction of internal structural images based on the varying attenuation of energy across different tissues. MRI offers several advantages, including the absence of ionizing radiation, making it a safe, non-invasive, rapid, and highly accurate clinical diagnostic modality. It provides detailed diagnostic information, such as the ability to differentiate between benign and malignant tumors.

Phototherapy, which induces apoptosis or necrosis in tumor tissues, is characterized by low toxicity to surrounding normal tissues. MRI plays a critical role in phototherapy by confirming the tumor’s location and size in vivo, thereby enabling both diagnostic evaluation and real-time treatment monitoring. In recent years, a variety of multifunctional composite nanoparticles that combine photothermal properties with MRI contrast capabilities have been developed, offering promising applications for integrated tumor diagnosis and therapy [4].

4. Development and innovation of therapeutic imaging technology

4.1. Introduction and integration of emerging imaging technologies

In recent years, the rapid advancement of therapeutic imaging technologies has given rise to emerging modalities such as photoacoustic imaging, ultra-resolution microscopy, and multimodal fusion imaging. These innovations have significantly overcome traditional limitations, greatly enhancing the capabilities of early disease diagnosis and precise therapeutic intervention. The integration of AI has further optimized image processing workflows, while the application of nanoprobes and molecular imaging technologies has enabled visualization at the cellular and even molecular levels [5]. Together, these advances facilitate real-time intraoperative navigation and contribute to the development of more efficient, low-risk, and integrative diagnostic and therapeutic systems—paving the way toward personalized medical care.

In particular, generative AI is proving to be a transformative force in medical imaging. It enables the denoising of low-dose CT scans, enhances the spatial resolution of MRI images, and reconstructs incomplete datasets from partial scans [5]. These improvements not only increase diagnostic accuracy but also reduce the need for repeat imaging, thereby minimizing patient radiation exposure and lowering healthcare costs. Perhaps most compelling is the potential of generative AI in predictive oncology: by analyzing current imaging data and simulating possible future scenarios, such models can forecast tumor progression and treatment response patterns, offering a powerful tool for anticipatory clinical decision-making [5].

4.2. Challenges and prospects of therapeutic imaging

Imaging technology is progressing toward higher resolution, real-time capabilities, and reduced radiation exposure, aligning with the broader goals of safety, accuracy, and efficiency in clinical practice. Simultaneously, the digitization of healthcare is fundamentally transforming clinical workflows by granting healthcare providers and patients greater access to data-driven insights. This shift marks a transition from experience-based medicine to an evidence-based, patient-centered approach. As AI technology evolves rapidly, both clinicians and researchers must prepare for a new era of data-driven, predictive, and personalized care [6]. Accordingly, medical education adapts to include not only life sciences and clinical knowledge, but also advanced training in statistics, data science, and computational methods. Notably, some medical schools have already integrated AI-focused courses into their curricula.

The implementation of AI in healthcare is becoming increasingly accessible due to the proliferation of open-source software tools and the widespread availability of cloud computing resources, accelerating their integration into clinical and research settings [6].

4.3. Limitations of artificial intelligence

While AI has significantly streamlined many aspects of daily life, its application in healthcare still requires careful consideration. The effectiveness of AI algorithms depends heavily on the diversity and comprehensiveness of the training data. Consequently, AI systems may demonstrate limited reliability in diagnosing or managing rare conditions and may underperform in populations that are underrepresented in the datasets [7]. Privacy and security concerns also remain paramount, as AI systems often rely on large-scale patient data, which may be vulnerable to unauthorized access or misuse. Furthermore, AI systems lack inherent accountability; responsibility for clinical outcomes remains diffuse and is influenced by the transparency of the algorithms, the quality of the training data, and the decisions made by developers and users [7]. This underscores the urgent need for well-defined regulatory frameworks and ethical guidelines to govern the responsible development and deployment of AI in medical settings. Despite these challenges, the integration of AI into healthcare continues to expand rapidly. Therefore, it is imperative to focus on designing robust, transparent, and ethically sound AI systems to ensure that their growing influence enhances, rather than compromises, the quality, safety, and equity of healthcare delivery [7].

5. Conclusion

Therapeutic imaging technology plays an essential role in oncology by enabling precise tumor localization, staging, and real-time treatment monitoring. Modalities such as CT, MRI, and PET offer detailed anatomical and metabolic data that inform accurate diagnosis and guide tailored therapeutic strategies. Molecular imaging further advances precision medicine by identifying tumor-specific markers and enabling personalized interventions.

Integrated imaging approaches—combining structural, functional, and molecular information—enhance diagnostic accuracy and treatment targeting. In radiotherapy, image-guided and adaptive techniques rely heavily on high-resolution imaging to optimize dose delivery and improve outcomes.

Emerging developments, such as AI-driven imaging analysis and theranostic radionuclide probes, promise to make imaging more intelligent, predictive, and therapeutic. These innovations will support prognosis prediction, therapy adjustment, and drug development.

Realizing the full potential of therapeutic imaging will require sustained interdisciplinary collaboration across medical imaging, molecular biology, computer science, and engineering—bridging research and clinical practice to transform cancer diagnosis and treatment.

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