World Journal of Biology Pharmacy and Health Sciences
eISSN: 2582-5542
Cross Ref DOI: 10.30574/wjbphs
Journal homepage: https://wjbphs.com/

(REVIEW ARTICLE)

Check for updates

Review: cutting-edge developments in radiotherapy: Advances in imaging, motion management and AI-driven treatment optimization

Ahmed Hasan Al-Jalawee *

Ahl Al BAYT University, Anesthesia and Intensive Care Techniques Department, College of Health and Medical Science, Karbala, Iraq.

World Journal of Biology Pharmacy and Health Sciences, 2025, 21(03), 012-017

Publication history: Received on 31 December 2024; revised on 15 February 2025; accepted on 18 February 2025

Article DOI: https://doi.org/10.30574/wjbphs.2025.21.3.0176

Abstract

Radiotherapy has long been a cornerstone in cancer treatment, utilizing ionizing radiation to target and destroy malignant cells. Recent technological and biological advancements have significantly enhanced treatment precision, reduced radiation exposure to healthy tissues, and improved patient outcomes. This review explores key innovations in radiotherapy, focusing on imaging advancements, motion management techniques, and artificial intelligence (AI)-driven treatment optimization. MRI-guided radiotherapy (MRgRT) has revolutionized tumor visualization, allowing real-time adaptation to anatomical changes, improving hypofractionation treatments, and enhancing therapeutic effectiveness. However, challenges such as magnetic field interference, extended planning times, and MRI contrast variability necessitate further research. Additionally, PET-CT and functional imaging have improved tumor delineation, optimized radiation dose distribution, and facilitated adaptive radiotherapy planning, particularly in lymphomas and rectal cancer treatment. AI has emerged as a transformative tool in radiotherapy, offering innovative solutions for motion tracking, tumor monitoring, and real-time treatment adaptation. AI-driven motion management strategies, including markerless tracking, full anatomy monitoring, and predictive modeling, enhance treatment precision by compensating for organ and tumor motion, reducing dose uncertainties, and improving radiation targeting. Surface Guided Radiation Therapy (SGRT) has further contributed to improving patient positioning, continuous motion monitoring, and adaptive treatment strategies. Its application in proton therapy, pediatric oncology, and accelerated partial breast irradiation (APBI) highlights its versatility in modern radiotherapy. Future research should focus on refining SGRT methodologies, integrating advanced surface mapping technologies, and expanding its role in adaptive radiotherapy planning. As radiotherapy continues to evolve, integrating cutting-edge imaging, AI-based tracking, and adaptive treatment approaches will be crucial in optimizing cancer treatment. While challenges remain, ongoing interdisciplinary collaborations will drive further innovations, ultimately improving survival rates and quality of life for cancer patients.

Keywords: MRIgRT; SGRT; PET-CT; AI-Based Motion Tracking

1. Introduction

Radiotherapy has long been a cornerstone in the treatment of cancer, utilizing ionizing radiation to target and destroy malignant cells. Recent advancements in the field have focused on improving precision, reducing side effects, and enhancing therapeutic outcomes through technological innovations and biological discoveries. Approximately 470,000 patients undergo radiotherapy annually in the United States[1]. Additionally, nearly half of all cancer patients receive this form of treatment[2]. Advances in diagnosis, therapeutic modalities, and supportive care have contributed to a significant increase in cancer survivorship[3]. Consequently, the focus of radiation oncology has expanded beyond achieving curative outcomes to mitigating adverse effects, particularly late-onset complications, which can profoundly impact patients' quality of life. Radiotherapy is employed in the management of both benign and malignant conditions, either as a

* Corresponding author: Ahmed Hasan Al-Jalawee.

standalone treatment or in conjunction with chemotherapy, surgery, or both. For primary tumors or metastatic lesions, palliative radiotherapy is frequently utilized to alleviate pain or mitigate mass effects associated with spinal cord compression, brain metastases, or airway obstruction. Therapeutic radiation can be administered through various modalities, including external-beam radiation therapy (EBRT), brachytherapy in which radioactive sources are implanted within cavities or tissues or systemic delivery of radiopharmaceutical agents. Over recent years, substantial technological and biological advancements have fundamentally reshaped the field of radiation oncology, leading to significant refinements in clinical practice[4].

2. Latest Technological Advancements in Imaging and Targeting of Radiotherapy

2.1. MRI-guided radiotherapy (MRIgRT)

Indrin J Chetty at all, reviewed the clinical applications and challenges associated with using MRI-guided radiotherapy (MRgRT) for the treatment of oligometastases. They highlighted that MRgRT offers improved soft tissue contrast, real-time imaging, and the ability to adapt radiation treatment dynamically during sessions[5]. These advantages enable increased radiation doses targeted at tumors while minimizing the impact on surrounding healthy tissues.

However, MRgRT faces challenges related to the need for more clinical evidence, as well as technical considerations involving planning, delivery, quality assurance for high-dose treatments, and safety in the MRI environment. The preliminary findings indicated that MRgRT is safe and effective in treating oligometastases using stereotactic body radiotherapy (SBRT) across multiple treatment sites, necessitating further clinical studies to validate its benefits.

Magnetic Resonance Imaging-Guided Radiation Therapy (MRgRT) enhances tumor targeting accuracy by providing clear visualization of soft tissues, reducing radiation exposure to healthy tissues. It also enables real-time adaptation to anatomical changes, improving the effectiveness of hypofractionation treatment and reducing the number of required sessions. Additionally, functional imaging can be utilized to enhance treatment response and deliver more precise and flexible radiation plans[6].

Christopher Kurz and all, explored the physical and medical challenges associated with MR-guided radiotherapy (MRgRT). The researchers concluded that integrating magnetic resonance imaging (MRI) with radiation therapy planning represents a significant advancement but presents several difficulties. One of the primary challenges is the influence of the magnetic field on the trajectory of charged particles, which may impact the accuracy of dose delivery. Additionally, precise calibration between imaging and treatment is essential to ensure optimal tumor alignment and minimize the effects of internal organ motion[7]. The study also highlighted the need for advanced models and algorithms to enhance real-time image processing and treatment planning. Another key challenge is the variability in MRI contrast, which affects tumor boundary delineation, necessitating improved dose estimation methods within the magnetic environment. To address these issues, the researchers emphasized the importance of developing corrective strategies and enhancing interdisciplinary collaboration among medical physicists, clinicians, and engineers to refine treatment efficiency while minimizing adverse effects on healthy tissues[7].

The study highlighted that MRI-guided radiotherapy enhances treatment accuracy by providing high-resolution, real-time imaging of tumors and surrounding tissues, reducing radiation exposure to healthy tissue. This technology enables real-time monitoring of organ movement, allowing for daily treatment adjustments based on anatomical changes. However, challenges remain, including increased time required for dose adaptation and difficulties in interpreting functional imaging changes. The researchers concluded that while MRI guidance is promising, further research is needed to optimize its clinical integration [8].

2.2. PET-CT and functional imaging

Rosa, Consuelo, et al.[9] in "DWI-MR and PET-CT Functional Imaging for Boost Tumor Volume Delineation in Neoadjuvant Rectal Cancer Treatment", researchers found that diffusion-weighted magnetic resonance imaging (DWI-MR) produced smaller target volumes compared to other imaging techniques such as computed tomography (CT), conventional T2-weighted magnetic resonance imaging (T2-MR), and positron emission tomography combined with computed tomography (PET-CT). Additionally, the results indicated that DWI-MR may be the optimal strategy for defining the target tumor volume to enhance radiation dose delivery in patients with locally advanced rectal cancer. These findings suggest that using DWI-MR can improve the accuracy of tumor volume delineation, potentially leading to enhanced radiotherapy effectiveness for this patient group [9].

McKay, Michael J., et al.[10] investigated the role of positron emission tomography combined with computed tomography (PET/CT) in improving the accuracy of radiotherapy planning for patients with lymphomas. The results showed that using PET/CT allows for more precise identification of biologically active tumor regions, leading to improved accuracy in targeting radiation fields and reducing the exposure of healthy tissues to radiation. Additionally, PET/CT enables the early assessment of a patient's response to chemotherapy, allowing for treatment plan adjustments based on the patient's response. This approach can enhance treatment outcomes and reduce side effects. Furthermore, PET/CT is used to evaluate treatment response and determine whether adjustments to the radiotherapy plan are necessary. This helps in providing more precise and effective treatment for lymphoma patients. Based on these findings, the researchers recommended integrating PET/CT into clinical practices for radiotherapy planning in lymphomas due to its role in improving treatment accuracy and minimizing potential side effects[10].

Caruso, Damiano, et al.[11] investigated the role of computed tomography texture analysis (CTTA) in improving the accuracy of diagnosing pulmonary nodules. The results showed that CTTA is a promising tool for distinguishing between benign and malignant pulmonary nodules, even in cases where there is no disruption in glucose metabolism. These findings suggest that CTTA can provide additional information beyond conventional PET/CT, contributing to improved diagnostic accuracy and reducing the need for invasive procedures such as biopsies[11].

Trotter, Jacob, et al[12]. examined the role of various PET tracers and the integration of PET/CT data into radiation therapy planning. The study concluded that incorporating PET/CT enhances the accuracy of radiation target delineation, thereby reducing exposure to healthy tissues and ultimately improving treatment outcomes. The findings indicated that a diverse range of PET tracers is available, targeting different metabolic pathways in cancer, allowing for a more comprehensive assessment of tumor biology. The researchers also discussed various methods for integrating PET/CT data into radiation therapy planning, including cognitive fusion, rigid registration, deformable registration, and PET/CT simulation techniques. Furthermore, the study highlighted several advantages of PET imaging in radiation therapy planning, such as improving the precision of tumor target delineation, enabling automated target definition, reducing inter-observer variability, and identifying high-risk tumor areas that may benefit from dose escalation or adaptive protocols. However, the study also acknowledged certain technical and biological limitations associated with the use of PET/CT in guiding radiation therapy, which should be carefully considered. Based on these findings, the researchers recommended the integration of PET/CT into clinical practice for radiation therapy planning, emphasizing its role in enhancing the accuracy of tumor targeting, minimizing potential side effects, and ultimately improving therapeutic outcomes for patients[12].

Abba Mallum and colleagues[13], the researchers explored the applications of PET/CT in radiation therapy planning across different types of cancer. The study highlighted that PET/CT has revolutionized radiation therapy planning for several malignancies. While its benefits have been well established and integrated into routine clinical practice for certain cancers, its role remains experimental for others. The review discussed the proven utility of PET/CT in cancers such as head and neck, cervical, brain, and lung malignancies, where it has been shown to enhance the accuracy of tumor volume delineation and reduce radiation exposure to healthy tissues. However, in other malignancies, including uterine, ovarian, and prostate cancers, the role of PET/CT in radiation therapy planning is still under investigation. Ongoing research is evaluating its potential to improve treatment outcomes in these cases. Additionally, the review addressed the implementation of PET/CT in Africa, emphasizing both the challenges and opportunities associated with adopting this technology in resource-limited settings. The researchers concluded that PET/CT is a valuable tool in radiation therapy planning, with well-established benefits for certain malignancies and promising potential for others. They recommended further studies to define its role in additional cancer types and to enhance its accessibility in regions with limited medical resources[13].

2.3. AI-Based Motion Tracking

In their review article titled "A Review of Artificial Intelligence Applications for Motion Tracking in Radiotherapy," Adam Mylonas, Jeremy Booth, and Doan Trang Nguyen examine the role of artificial intelligence (AI) in managing intrafraction motion during radiotherapy. Intrafraction motion refers to the movement of organs and tumors during treatment, which can lead to underdosing of the tumor and overdosing of healthy tissues, ultimately compromising treatment efficacy and increasing patient toxicity. The review highlights how AI-based motion management techniques can enhance the precision of radiation delivery and improve patient outcomes. Authors categorize AI-based motion tracking strategies into four primary approaches. The first approach, marker-based tracking, involves implanting markers within or near the tumor to facilitate precise tracking during treatment. The second approach, markerless tracking, relies on imaging data to track the tumor or surrounding anatomical structures directly, eliminating the need for implanted markers. The third approach, full anatomy monitoring, utilizes AI algorithms to monitor the entire anatomical region within the field of view, ensuring comprehensive oversight of intrafraction motion. Finally, the fourth approach, motion prediction, leverages AI models to anticipate tumor and organ movement, compensating for system latencies in localization and processing, thereby improving the accuracy of radiation delivery[18]. The review emphasizes the potential of AI to enhance real-time image-guided radiation therapy (IGRT) by providing precise tumor tracking and motion compensation, leading to improved radiation dosing while minimizing exposure to healthy tissues. The authors advocate for continued research and technological advancements in AI applications to further refine motion management strategies in radiotherapy and optimize treatment effectiveness[14, 18].

The research paper "Real-time motion management in MRI-guided radiotherapy: Current status and AI-enabled prospects"[15] focuses on reviewing current solutions for motion management during MRI-guided radiotherapy (MRIgRT) sessions and provides insights into how these processes can be enhanced using artificial intelligence (AI). The study highlights existing techniques such as real-time imaging, which utilizes MRI to track organ and tissue movement during therapy, enabling the adjustment of radiation beams accordingly. It also discusses tracking methods, including marker-based and markerless tracking[17, 15]. Marker-based tracking requires inserting markers into the patient's body, whereas markerless tracking relies on natural anatomical features. Furthermore, the paper addresses beam adaptation, where real-time modifications are made to radiation beams based on movement data to ensure precise targeting of tumors while minimizing exposure to healthy tissues. The paper emphasizes the role of AI in enhancing tracking speed and accuracy by analyzing large volumes of real-time imaging data, allowing for more precise organ movement tracking. Additionally, motion prediction techniques using machine learning algorithms help anticipate organ shifts based on past patterns, enabling proactive radiation beam adjustments. AI also contributes to reducing processing time, making real-time adaptations more efficient. Despite these advancements, the study highlights challenges and future prospects in integrating AI into clinical practices. Ensuring safety and effectiveness requires further studies, and medical teams must receive proper training and acceptance to implement AI-driven techniques. The paper underscores the need for further research to develop more advanced algorithms capable of adapting to diverse motion scenarios[15, 16].

2.4. Surface Guided Radiation Therapy (SGRT)

2.4.1. Diverse Clinical Applications

The researchers highlighted that SGRT is used in a wide range of clinical applications, including: Patient positioning with real-time feedback: This ensures precise patient setup before starting treatment. Continuous patient monitoring during treatment sessions: This helps detect any unintended patient movements and adjust accordingly. Motion management: Techniques like Deep Inspiration Breath Hold (DIBH) help reduce internal organ movement during treatment. These applications contribute to improving treatment accuracy and minimizing exposure to healthy tissues[19, 20].

2.4.2. Specialized Techniques

The article explored SGRT's role in advanced radiotherapy techniques, including: Accelerated Partial Breast Irradiation (APBI): SGRT ensures precise targeting of the affected area while reducing radiation exposure to surrounding healthy tissues. Proton therapy: SGRT improves the accuracy of proton beam delivery to tumors. Pediatric cancer treatment: SGRT helps reduce the need for general anesthesia by shortening treatment sessions and enhancing targeting accuracy. These techniques enhance treatment effectiveness and reduce potential side effects [19].

2.4.3. Future Research Directions

The article discussed potential future research areas in SGRT, including:

Using deformable surfaces as motion indicators to track internal organ movements more accurately. Utilizing SGRT to detect anatomical changes during the course of treatment, allowing for adaptive treatment planning. Contributing to personalized treatment plans by refining safety margins and motion management strategies based on individual patient needs. Enhancing patient safety by integrating measures to minimize common radiotherapy errors, such as facial recognition and treatment accessories[19].

3. Conclusion

Radiotherapy remains a cornerstone in cancer treatment, with continuous advancements aimed at enhancing precision, minimizing side effects, and improving patient outcomes. Recent innovations in imaging, motion management, and artificial intelligence have revolutionized radiation oncology, enabling more effective and personalized treatment approaches.

MRI-guided radiotherapy (MRgRT) has significantly improved tumor visualization, allowing for real-time adaptation to anatomical changes and reducing radiation exposure to healthy tissues. However, challenges such as magnetic field interference, extended planning times, and the need for better dose estimation methods remain areas for further research. Similarly, PET-CT and functional imaging have proven instrumental in refining tumor delineation, reducing treatment toxicity, and facilitating adaptive radiotherapy planning, particularly in conditions like lymphomas and rectal cancer.

The integration of AI in radiotherapy has opened new frontiers in motion tracking and real-time treatment adaptation. AI-based solutions, including markerless tracking, full anatomy monitoring, and predictive modeling, enhance precision by compensating for organ and tumor motion, ultimately reducing treatment uncertainties. Despite these advancements, ensuring seamless clinical integration, overcoming technical limitations, and maintaining safety remain critical challenges requiring further investigation.

Surface Guided Radiation Therapy (SGRT) has emerged as a valuable tool in patient positioning, continuous motion monitoring, and adaptive treatment strategies. Its application in proton therapy, pediatric oncology, and accelerated partial breast irradiation (APBI) underscores its versatility. Future research should focus on refining SGRT methodologies, integrating advanced surface mapping techniques, and expanding its role in adaptive radiotherapy.

As technology continues to evolve, radiotherapy is shifting towards more precise, patient-centered, and adaptive treatment paradigms. While challenges persist, ongoing interdisciplinary collaboration among medical physicists, radiation oncologists, and AI researchers will be pivotal in optimizing radiotherapy techniques, ultimately improving survival rates and quality of life for cancer patients.

References

[1] Cancer Moonshot Blue Ribbon Panel. Report 2016. Bethesda, MD: National Cancer Institute, October 17, 2016

[2] DeVita VT Jr, Lawrence TS, Rosenberg SA. DeVita, Hellman, and Rosenberg's Cancer: principles and practice of oncology. 10th ed. Philadelphia: Lippincott Williams & Wilkins, 2014.

[3] Cancer treatment and survivorship facts &figures 2016-2017. American Cancer Society, 2012).

[4] Lichter, AS, Lawrence, TS. Recent advances in radiation oncology. *N Engl J Med* 1995;332:71-379

[5] Chetty IJ, Doemer AJ, Dolan JL, Kim JP, Cunningham JM, Dragovic J, Feldman A, Walker EM, Elshaikh M, Adil K, Movsas B, Parikh PJ. MRI-guided Radiotherapy (MRgRT) for Treatment of Oligometastases: Review of Clinical Applications and Challenges. Int J Radiat Oncol Biol Phys. 2022 Dec 1;114(5):950-967. doi: 10.1016/j.ijrobp.2022.07.027. Epub 2022 Jul 25. PMID: 35901978.

[6] Gough J, Hall W, Good J, Nash A, Aitken K. Technical Radiotherapy Advances - The Role of Magnetic Resonance Imaging-Guided Radiation in the Delivery of Hypofractionation. Clin Oncol (R Coll Radiol). 2022 May;34(5):301-312. doi: 10.1016/j.clon.2022.02.020. Epub 2022 Mar 16. PMID: 35305888.

[7] Kurz C, Buizza G, Landry G, Kamp F, Rabe M, Paganelli C, Baroni G, Reiner M, Keall PJ, van den Berg CAT, Riboldi M. Medical physics challenges in clinical MR-guided radiotherapy. Radiat Oncol. 2020 May 5;15(1):93. doi: 10.1186/s13014-020-01524-4. PMID: 32370788; PMCID: PMC7201982.

[8] Corradini S, Alongi F, Andratschke N, Belka C, Boldrini L, Cellini F, Debus J, Guckenberger M, Hörner-Rieber J, Lagerwaard FJ, Mazzola R, Palacios MA, Philippens MEP, Raaijmakers CPJ, Terhaard CHJ, Valentini V, Niyazi M. MR-guidance in clinical reality: current treatment challenges and future perspectives. Radiat Oncol. 2019 Jun 3;14(1):92. doi: 10.1186/s13014-019-1308-y. PMID: 31167658; PMCID: PMC6551911.

[9] Rosa, Consuelo, et al. "DWI-MR and PET-CT functional imaging for boost tumor volume delineation in neoadjuvant rectal cancer treatment." *in vivo* 37.1 (2023): 424-432.

[10] McKay, Michael J., et al. "Radiotherapy planning of lymphomas: role of metabolic imaging with PET/CT." *Annals of Nuclear Medicine* (2022): 1-10.

[11] Caruso, Damiano, et al. "Radiomics and functional imaging in lung cancer: the importance of radiological heterogeneity beyond FDG PET/CT and lung biopsy." *European Journal of Radiology* 142 (2021): 109874.

[12] Trotter, Jacob, et al. "Positron emission tomography (PET)/computed tomography (CT) imaging in radiation therapy treatment planning: a review of PET imaging tracers and methods to incorporate PET/CT." *Advances in radiation oncology* 8.5 (2023): 101212.

[13] Mallum, Abba, et al. "The role of positron emission tomography and computed tomographic (PET/CT) imaging for radiation therapy planning: a literature review." *Diagnostics* 13.1 (2022): 53.

[14] Mylonas, Adam, Jeremy Booth, and Doan Trang Nguyen. "A review of artificial intelligence applications for motion tracking in radiotherapy." *Journal of Medical Imaging and Radiation Oncology* 65.5 (2021): 596-611.

[15] Lombardo, Elia, et al. "Real-time motion management in MRI-guided radiotherapy: Current status and AI-enabled prospects." *Radiotherapy and Oncology* 190 (2024): 109970.

[16] Videtic GMM, Donington J, Giuliani M et al. Stereotactic body radiation therapy for early-stage non-small cell lung cancer: Executive Summary of an ASTRO Evidence-Based Guideline. Pract Radiat Oncol 2017; 7: 295–301

[17] Morgan SC, Hoffman K, Loblaw A et al. ASTRO/ASCO/ AUA guideline on hypofractionation for localized prostate cancer. Practical Radiation Oncology 2018; 8: 354–60

[18] Videtic GMM, Donington J, Giuliani M et al. Stereotactic body radiation therapy for early-stage non-small cell lung cancer: Executive Summary of an ASTRO Evidence-Based Guideline. Pract Radiat Oncol 2017; 7: 295-301.

[19] Freislederer, P., Kügele, M., Öllers, M. *et al.* Recent advances in Surface Guided Radiation Therapy. *Radiat Oncol* 15, 187 (2020). https://doi.org/10.1186/s13014-020-01629-w

[20] Brahme A, Nyman P, Skatt BB. 4D laser camera for accurate patient positioning, collision avoidance, image fusion and adaptive approaches during diagnostic and therapeutic procedures. Med Phys. 2008;35(5):1670.