Present and future role of MRI in radiotherapy

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Abstract

This paper explores the integration of MRI into modern clinical radiotherapy practice, examining its potential to enhance treatment precision, efficiency, and improve patient outcomes. The study offers an overview of MRI applications, including radiotherapy planning, image registration, quality assurance with an emphasis on reducing geometric distortions, and real-time adaptive MRI-guided radiotherapy. The introduction covers the use of MRI in treatment planning, followed by a description of its role during therapy, emphasizing functional imaging techniques and motion control. Dosimetric requirements, CT replacement techniques, and adaptive MRI-guided real-time radiotherapy are also discussed. The paper also presents early results obtained from MRI-linear accelerators, discussing technical challenges and the current status of these devices. Finally, by analyzing various scientific articles, the future role of magnetic resonance imaging in radiotherapy is considered, and conclusions are drawn based on the analyses and results collected.

Keywords: Adaptive Radiotherapy; MRIgRT; MR-linear accelerator; modern radiotherapy

Abbreviations and acronyms: ART – Adaptive Radiotherapy, **CBCT** – Cone Beam Computed Tomography, **CT** – Computed Tomography, **CTV** – Clinical Target Volume**, DVH –** Dose-Volume Histogram, **FOV** – Field of View, **GTV** – Gross Tumor Volume, **MRI** – Magnetic Resonance Imaging, **MRIgRT** – Magnetic Resonance Image-guided Radiotherapy, **MRI-LINAC –** MRI-Linear Accelerator system, **OAR** – Organs at Risk, **PTV** – Planning Target Volume**, QA –** Quality Assurance, **RF** – Radiofrequency, **RT** – Radiotherapy, **RTP** – Radiation Treatment Planning**, SBRT** – Stereotactic Body Radiation Therapy, **SCT** – Synthetic Computed Tomography, **SNR** – Signal-to-Noise Ratio, **SRS** – Stereotactic Radiosurgery

Introduction

Over the past century, a significant decline in cancer mortality rates has been observed [1], with the exception of certain aggressive malignancies such as glioblastoma and pancreatic cancer. This trend is closely associated with advances in treatment, particularly in the field of radiotherapy (Figure 1), which has become very important, often in combination with chemotherapy. Radiotherapy is applicable to approximately 60% of oncology patients and continues to evolve through technological advancements and innovations in treatment planning and delivery [1]. In modern oncology, Magnetic Resonance Imaging is gaining an increasingly prominent role, not only in the treatment planning but also during the execution of therapy (Figure 2) [2]. Advances in high-resolution imaging, superior soft tissue contrast, and real-time monitoring capabilities contribute to more precise dose delivery, reduced toxicity, and improved patient quality of life [3,4]. The radiotherapy workflow begins with patient preparation, including education about the procedure, immobilization, and positioning, followed by simulation using CT or MRI [2] (Figure 3). Based on these images, a radiation treatment plan

Figure 1: Linear accelerator
Source: https://trends.medicalexpo.com/varian-oncology/project-70440-414038.html

Figure 2. MRI Simulator for Radiotherapy Treatment Planning
Source: https://www.siemens-healthineers.com/radiotherapy/MR-for-rt

is developed, integrating previous diagnostic data. During therapy, image verification is ensured through CBCT comparing current images with those acquired during simulation. This process ensures the correct positioning of the clinical target volume (CTV) and maintains the radiation dose within prescribed limits [2]. In this context, the role of MRI is not merely supplementary but increasingly serves as a primary modality in radiotherapy planning, because of its capacity to provide detailed anatomical and functional information [5,6].

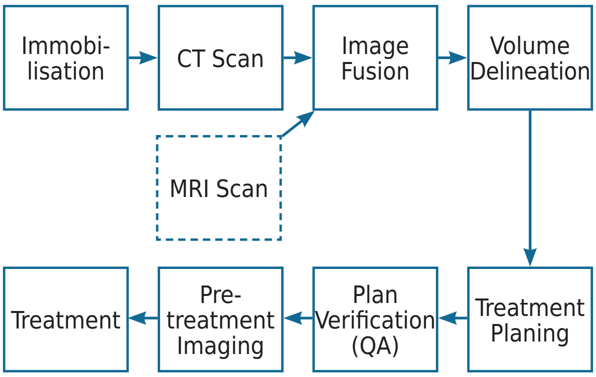


Figure 3. Radiotherapy Workflow
Source: https://pubmed.ncbi.nlm.nih.gov/30194794/

Radiotherapy planning workflow

Treatment Planning Systems (TPS): Core of planning, integrating imaging, dose calculations, and optimization [6,7].
Imaging & Simulation: High-quality CT, MRI, and PET imaging for accurate tumor and organ-at-risk (OAR) delineation [4,7].
Target Volume Definition:

- *GTV:* localize the tumor, guide the dose distribution, minimize the exposure to surrounding healthy tissues [4,7]
- *CTV*: includes microscopic spread
- *PTV*: adds margins for uncertainties

Dose Prescription & Constraints: Balancing dose to targets while minimizing exposure to OARs [3,7].
Treatment Techniques:

- *3D-CRT*, *IMRT*, *VMAT* for dose conformity
- *SRS/SBRT* for precision in small targets [4,7]

Motion Management: Techniques like gating, breath-hold, and adaptive planning for organ motion [4,7].
Quality Assurance: Ensuring treatment accuracy with conformity and safety checks [7].
Adaptive Radiotherapy: Adjusting plans based on anatomical changes during treatment [7].

MRI in radiotherapy treatment planning

Radiotherapy treatment planning requires precise delineation of the target volume and identification of critical structures to be protected. Advances in technology have led to the development of techniques such as SRS and SBRT, which improve treatment outcomes by reducing side effects and enhancing therapeutic efficacy [4]. The use of MRI in RTP offers multiple advantages [4,7]. Unlike CT, MRI provides superior soft tissue contrast, allowing more accurate contouring of tumors and surrounding healthy organs [7,8]. Despite initial challenges, such as reduced bone imaging capability and the lack of electron density information needed for dosimetric calculations, new MRI techniques including the use of dynamic contrast and diffusion sequences have improved tissue segmentation and therapy individualization [6]. In specific body regions, particularly the head, neck, and brain, MRI is already used independently (Figure 6). MRI images can serve as a secondary modality alongside CT during planning; however,

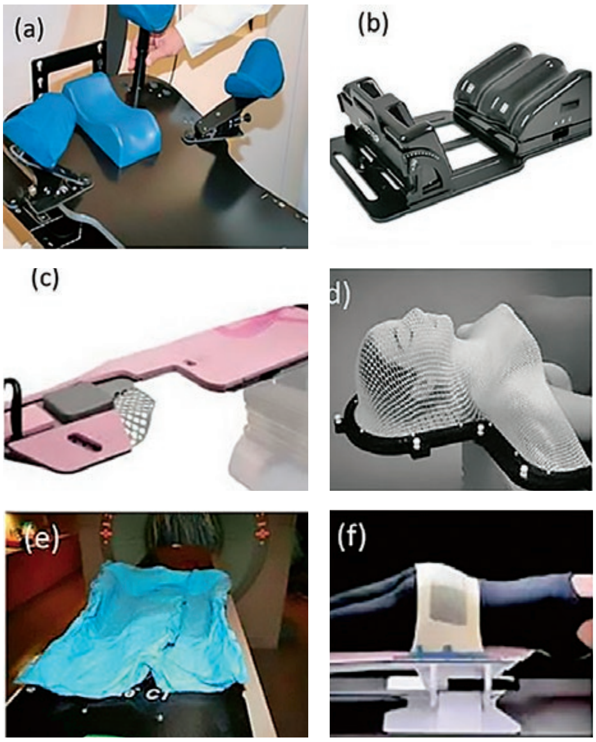


Figure 4. Immobilization devices in radiotherapy
Source: https://pubmed.ncbi.nlm.nih.gov/30194794/

more recently, planning is increasingly being performed only based on MRI images (Figure 5). A growing number of clinical studies confirm its utility and reliability [9]. Over the last decade, MRI has been increasingly utilized in radiotherapy, not only for planning but also for assessing treatment response. To streamline workflow, reduce patient

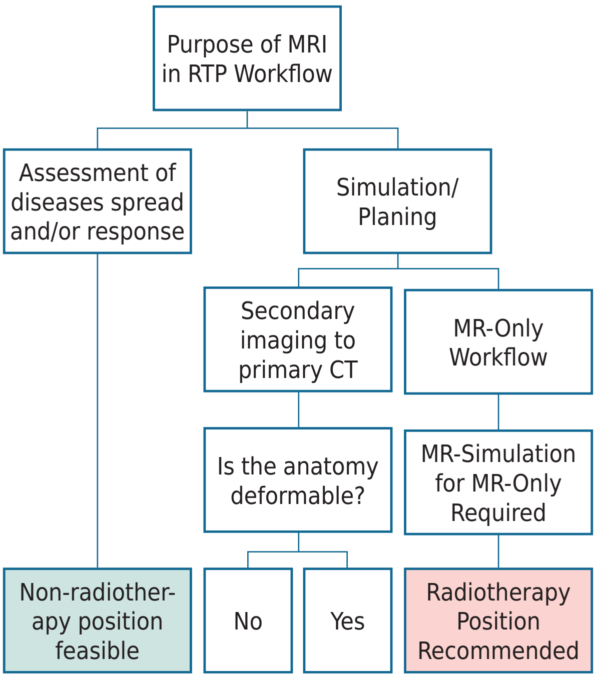


Figure 5. Guide for the use of the different imaging positions in RTP workflow
Source: Tijssen RHN, Paulson ES, Rai R. Implementation and Acquisition Protocols. MRI for Radiotherapy [Internet]. 2019;3–19.

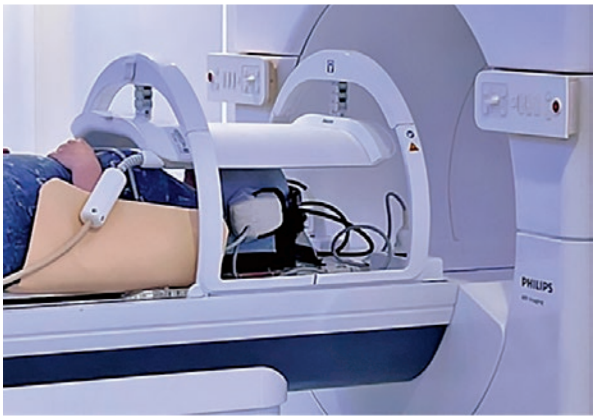
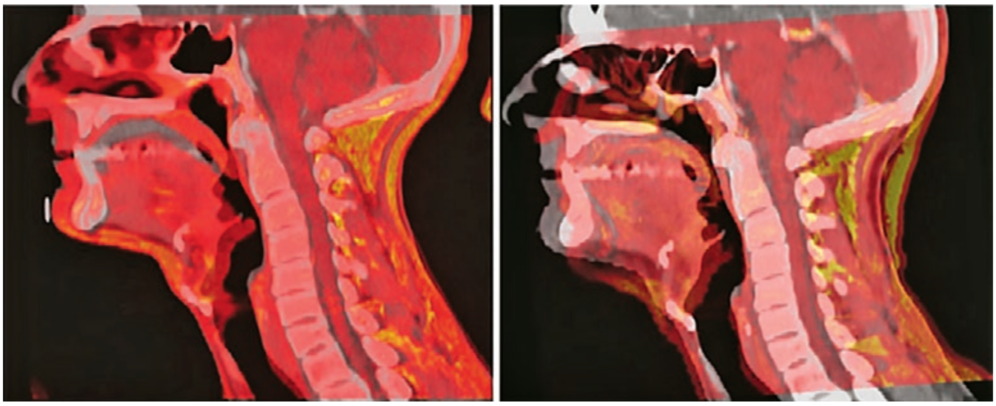


Figure 6. Example of a head and neck setup with the patient immobilisied using a thermoplastic mask and vacuum bag
Source: Jonsson, J.H., Karlsson M.G., Karlsson M., *et al*. Treatment planning using MRI data: an analysis of the dose calculation accuracy for different treatment regions. Radiat. Oncol. 2010 Jun 30;5:62. doi: 10.1186/1748-717X-5-62

dose, and ensure cost-effectiveness, it is logical to aim for a treatment planning process entirely based on MRI [10]. Radiotherapy planning also requires specific protocols for MRI equipment placement [11]. Rooms housing MRI equipment must meet strict criteria, including vibration protection and minimal electromagnetic interference. Safety protocols involve dividing spaces into zones (from Zone I—free access, to Zone IV—the highest risk area), ensuring only educated staff access specific zones [11]. Additionally, immobilization sets must be tailored to MRI devices, and their compatibility tested through internal protocols to minimize artifacts and ensure optimal image quality [6,11] (Figure 4). Successful integration of MRI into radiotherapy planning relies on collaboration between radiation oncologists, radiation therapists, and medical physicists [6,11]. Ongoing staff education and training are crucial to adapting to new technologies and maintaining safety standards. This approach facilitates effective use of MRI in planning, achieving more accurate target volume definition and reducing the risk of adverse side effects [6,7,11].

The integration of MRI into radiotherapy protocols presents challenges related to patient safety [6]. Before each MRI procedure, a thorough assessment of the patient's compatibility with the device is performed, including a review of implanted devices such as pacemakers and ICD [11]. Strict adherence to manufacturer guidelines is necessary for these patients to avoid adverse reactions such as overheating or current induction [11]. The use of contrast, particularly gadolinium, adds another level of complexity to safety protocols. Gadolinium enhances T1 contrast, but different types of contrast vary in their retention dynamics within the body. Therefore, laboratory tests, including an assessment of renal function, are required before contrast administration, and patients must be informed about potential side effects [11]. Another critical aspect of radiotherapy implementation is QA, which is of paramount importance. Specific requirements, such as patient positioning using flat table inserts and immobilization devices, directly impact MRI image quality [12]. QA protocols involve daily, weekly, monthly, and annual reviews. For radiotherapy imaging, a larger FOV is often required to encompass tumor volumes, organs at risk, and the external body contours. QA procedures typically uti-



Treatment position MRI **Diagnostic position MRI**

Figure 9. Images of a patient with an oropharyngeal squamous cell carcinoma, grey overlay images are CT, and red overlay are MRI. MRI images acquired in the treatment and diagnostic position
Source: Speight R., MRI to CT Image Registration. In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

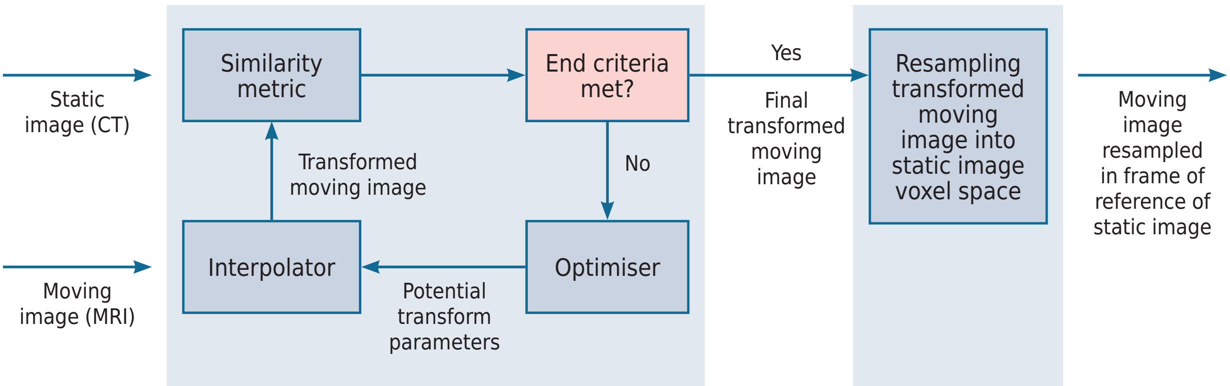
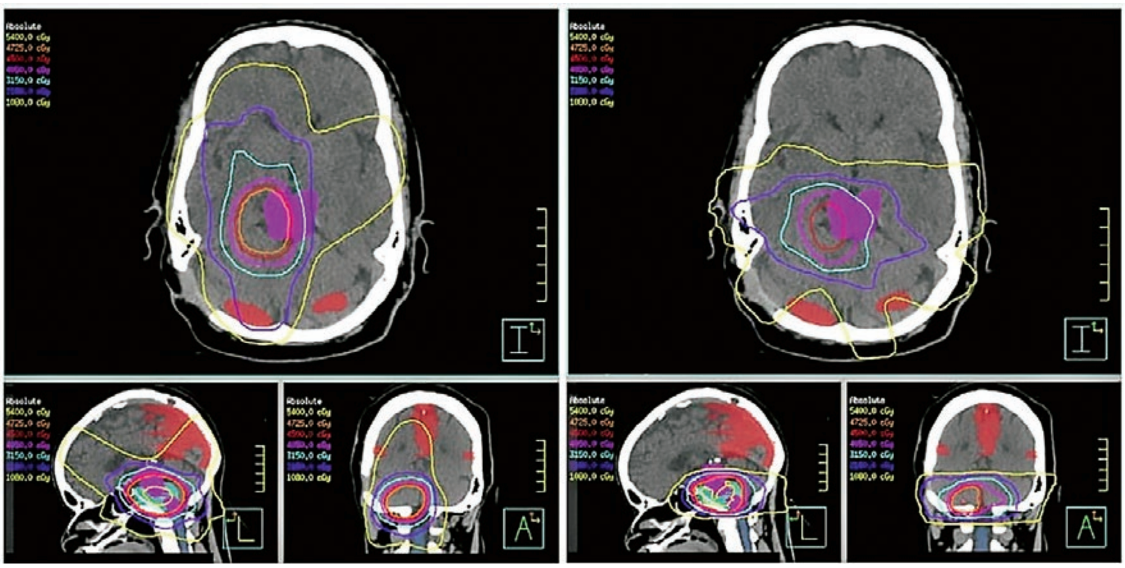


Figure 10. Schematic of the automatic image registration process
Source: Speight R., MRI to CT Image Registration. In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.



Standard care plan **fMRI DWN avoidance plan**

Figure 11. Comparison of standard radiotherapy (left) vs. fMRI-guided DMN avoidance (right), highlighting differences in dose distribution to protect brain function
Source: https://physicsworld.com/a/resting-state-fmri-fine-tunes-brain-radiotherapy-plans/

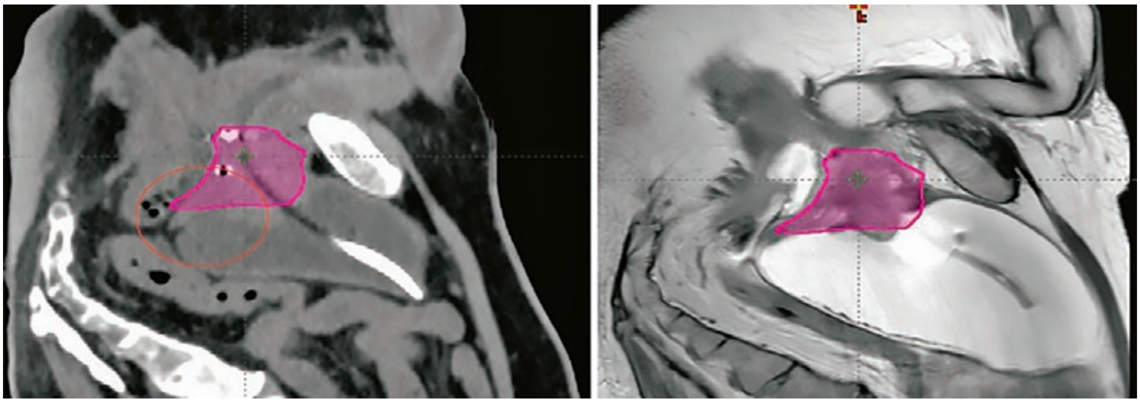


Figure 12. An example case when MRI is used as a secondary imaging modality
Source: Tyagi N., Challenges and Requirements, in: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

lize the ACR MR QA phantom along with commercial large FOV phantoms with geometric accuracy to assess image quality [12].

MRI during treatment

For effective implementation of MRI in radiotherapy, it is necessary to establish strict protocols for image registration [6]. The registration of MRI and CT images, or the fusion of data from both modalities, enables the transfer of specific structures from one image to another. Figure 9 displays MRI images obtained in both radiotherapy and diagnostic positions, where significant variations in the positioning of the neck and chin are visible [6]. However, due to the fundamental differences between MRI (which maps proton signals) and CT (which maps electron density), this process requires advanced algorithms and manual or automatic adjustments to achieve high precision [6]. Automated registration algorithms use optimization loops that adjust translations and rotations of the moving image, while manual registration depends on experienced staff who can further refine the results. This hybrid approach ensures that the registration is within acceptable error margins, thereby minimizing the risk of errors in dose delivery [6] (Figure 10).

The application of MRI in radiotherapy delivery opens up opportunities for monitoring anatomical changes in patients during treatment [6]. Functional MRI (fMRI) imaging provides visualization of physiological tissue characteristics, including vascularization, cell density, and metabolism, which is particularly valuable in assessing tumor response to radiation [13]. For instance, in the case of brain tumors, the integration of fMRI data enables more precise delineation of the tumor volume and allows for real-time dose adjustment, thereby enhancing disease control [13]. Figure 11 compares standard radiation therapy planning (left) with fMRI-guided DMN avoidance planning (right), showing differences in radiation dose distribution to preserve critical brain networks [13].

One of the most important challenges in radiotherapy delivery is organ motion during treatment [13]. In Figure 12, an example is shown where MRI is used as a secondary imaging modality. Variations in the bladder and rectum between CT and MRI resulted in different positions of the seminal vesicles [14]. Traditional CT techniques, due to their limited soft tissue contrast, often cannot accurately track patient movements, which may lead to deviations in

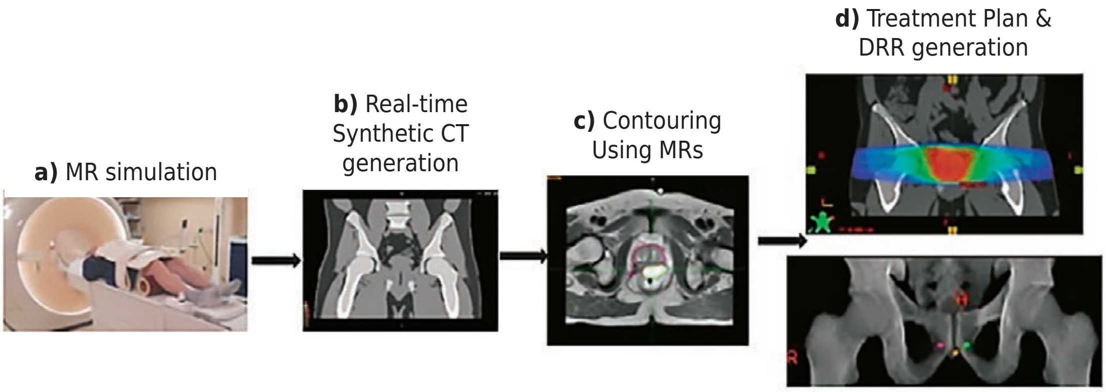


Figure 13. MRI-only workflow: (a) MR simulation. (b) Real-time synthetic CT generation. (c) Contouring using MRI. (d) Treatment plan and DRR generation
Source: Tyagi N., Challenges and Requirements, in: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

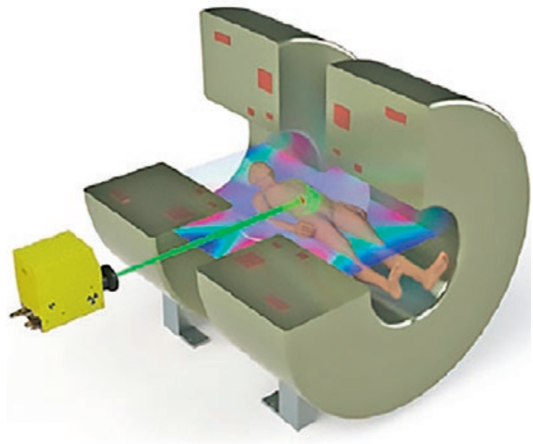
dose delivery. MRI, on the other hand, enables real-time motion tracking through high-frequency imaging, facilitating treatment adaptation during each fraction [14]. This approach, known as MRIgRT enables continuous verification of the position of the target volume and adjustment of plans in case of changes in anatomy [6,12,14,15].

Innovative approaches in radiotherapy delivery also include method where planning and treatment are based on MRI only modality [6,15] (Figure 13). This approach eliminates the need for additional MRI and CT image registration, thereby reducing the potential for errors, saving time, and decreasing patient exposure to radiation from CT devices [6,15]. Clinical experiences indicate that using an MRI-only protocol can enhance dose delivery precision and allow for dynamic treatment plan adaptation, particularly in tumors prone to changes during therapy. MRIgRT requires precise monitoring of the CTV [6,7-9,14-16]. MR-linear accelerators enable continuous high-frequency imaging, facilitating the detection and compensation of motion during therapy. Monitoring is typically performed in the sagittal plane, with parameters such as boundary expansion (defining the permissible space outside the target volume) and the region of interest for monitoring being established [7,16]. Incorporating audio or visual feedback further assists patients in maintaining a stable position, thus enhancing the accuracy of therapy [16].

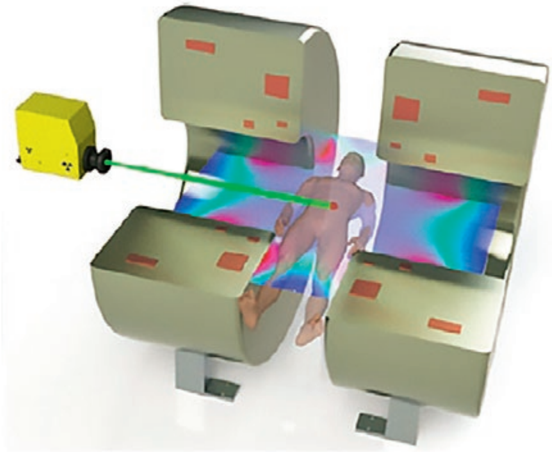
MRI-linac integration challenges

While MRI technology offers numerous advantages in radiotherapy, its integration into clinical practice presents a range of technical and logistical challenges [6,16,17]. One of the most significant challenges is synchronizing the MRI system with the linear accelerator. Operating a linear accelerator in proximity to an MRI device is particularly difficult due to electromagnetic interference between the two subsystems (MRI and linear accelerator) [16-22]. The magnetic fields generated by the MRI affect the electron trajectories in the accelerator according to the Lorentz law:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}),$$



a) Perpendicular configuration



b) In-line configuration

Figure 14. MRI-Linac systems in two possible configurations
Source: Whelan B., Oborn B., Liney G., Keall P., RI Linac Systems, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

System	Radiation type	Field strength	Magnet type	Orientation	Source-isocentre distance	First patient Tx
Elekta Unity	7 MV FFF	1.5 T	Closed superconducting	Perpendicular	1.47 m	May 2017
View Ray MRIdian	6 MV or ^{60}Co FFF	0.35 T	Split superconducting	Perpendicular	0.9 m	February 2014 (^{60}Co) July 2017 (Linac)
Magnet Tx Aurora	6MV	0.5 T	High temperature superconducting with steel yoke	In-line	1.4 m	Has not yet occurred
Australian MRI-Linac	4 & 6 MV FFF	1.0 T	Open superconducting	In- line with perpendicular option	1.8 m	Has not yet occurred

FFF flattening filter free, *MV* megavoltage, *Tx* treatment

Figure 15. Specifications of the existing MRI-Linacs
Source: Whelan B., Oborn B., Liney G., Keall P., RI Linac Systems, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019

where q is the electron charge, v is the velocity, B is the magnetic field, and F is the force acting on the electron [22]. These systems facilitate the simultaneous use of MRI imaging and radiation, enabling real-time therapy adaptation [21-23]. The configurations of MRI-linear accelerators can be either perpendicular or parallel, depending on the orientation of the magnetic field relative to the radiation beam [22]. In the perpendicular configuration, the magnetic field influences the electron path within the accelerator, potentially reducing the beam energy if the magnetic field is not adequately shielded [22]. In the parallel configuration, negative effects occur only at much higher magnetic field strengths (Figure 14). Therefore, it is essential to position the linear accelerator in a region where the magnetic field is minimal or apply appropriate shielding measures to ensure beam stability [11,22].

Adaptive radiotherapy

ART is a methodology that modifies patient treatment based on changes in target volumes and organs at risk (OARs) [23]. This approach enhances dose delivery precision to the tumor while simultaneously sparing the OARs from unnecessary exposure to the same dose. ART involves real-time image guided radiotherapy, accurate image registration, re-contouring of targets and OARs, treatment plan evaluation and re-optimization, as well as dosimetry andQA [23-26]. Adaptation can be performed offline, where new data is collected, and a new treatment plan is generated over hours or days, or online, where adjustments are made while the patient is on the treatment table during radiotherapy (Figure 16) [23-26].

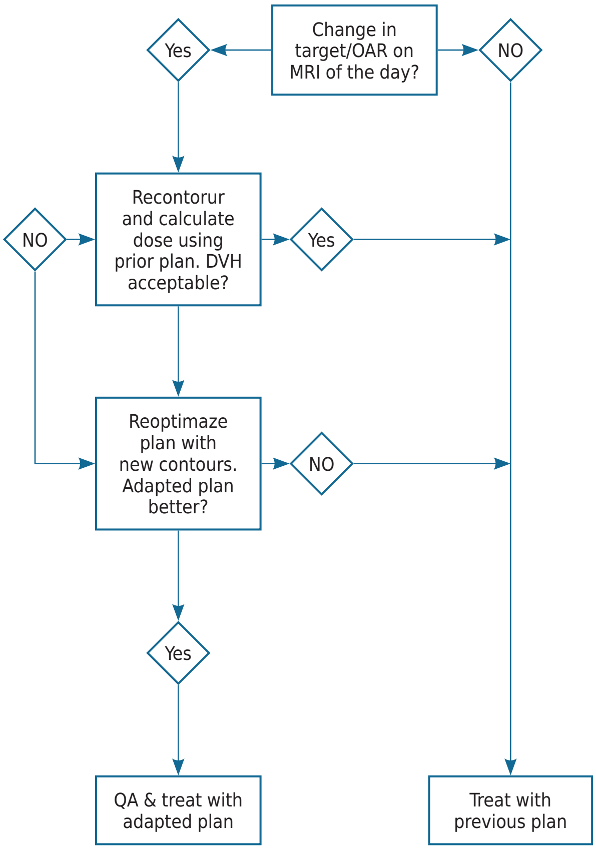


Figure 16. Example online adapted workflow: OAR, DVH, QA
Source: Roach M., Glide-Hurst C.K., MR at the time of External Beam Treatment In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

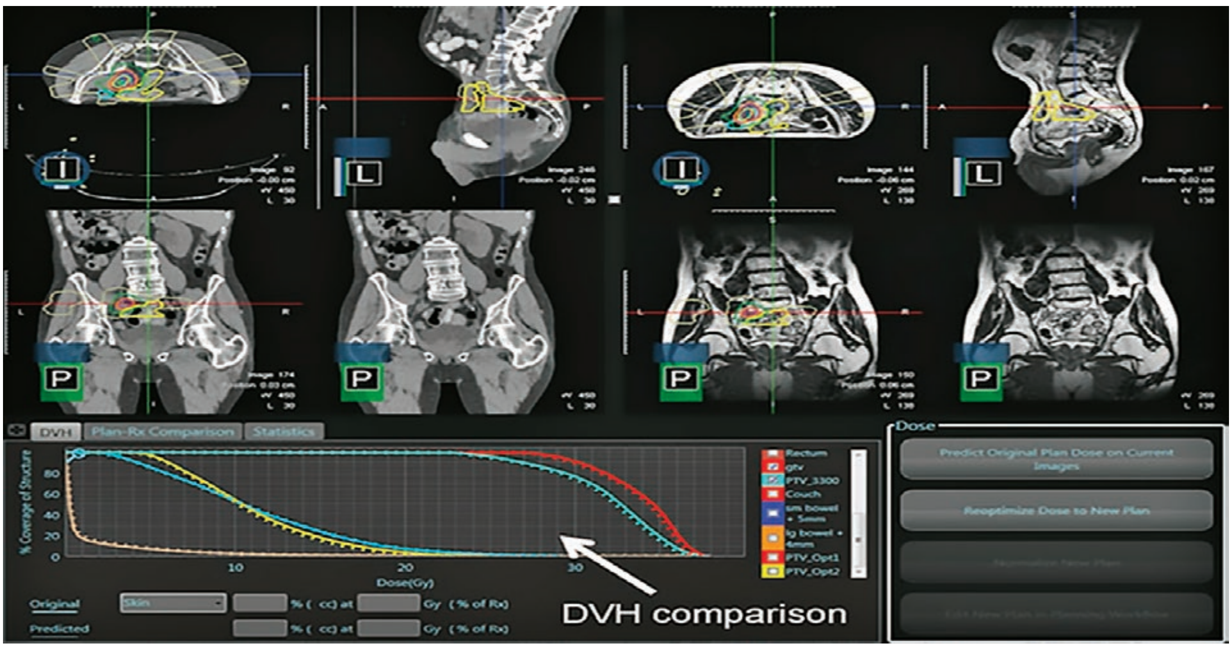


Figure 17. Comparison of original plan (four upper left CT images) on the original CT simulation scan, and the original plan's beams when calculated on the first day's MRI scan on ViewRay. The lower half of the panel shows a DVH showing the percent of structures receiving a certain dose
Source: Roach M., Glide-Hurst C.K., MR at the time of External Beam Treatment In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

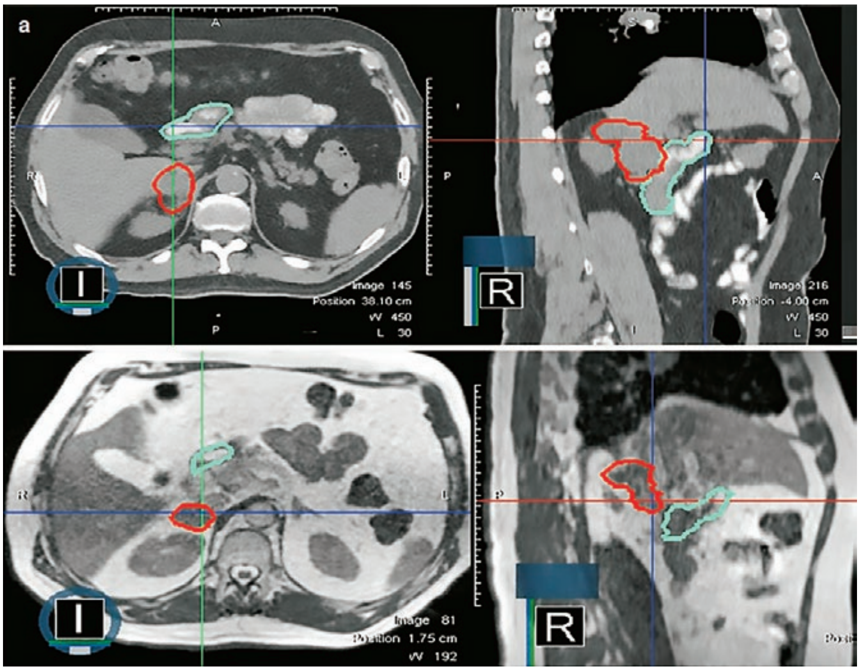


Figure 18. Online/on-table adaptation of a right adrenal target (red) on ViewRay. The top two panels are axial and sagittal slices of the simulation CT scan where nearby duodenum (cyan) is nearby. The bottom panels show that on the set-up MRI for the first day of treatment, the duo denum has shifted further away from the target, poten tially allowing for better dose coverage of the target
Source: Roach M., Glide-Hurst C.K., MR at the time of External Beam Treatment In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

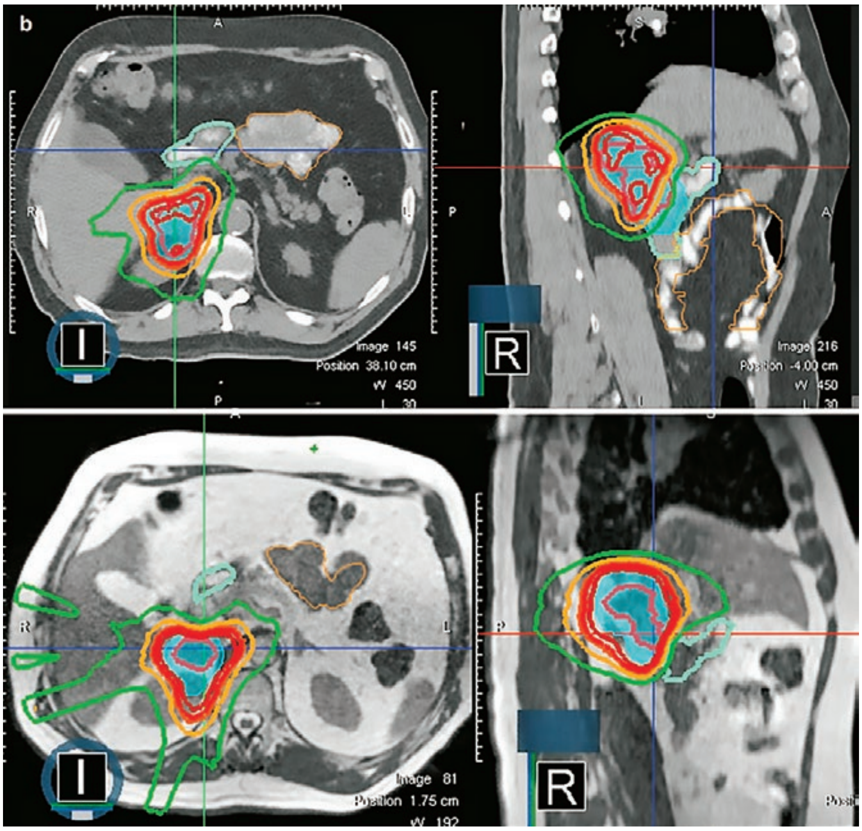


Figure 19. Online adaptation of a right adrenal target (blue color wash) on ViewRay. On the top panels, the original plan is shown where high dose coverage (orange and red) is limited due to target proximity to the duodenum (cyan). On the bottom panels, the plan has been adapted to increase coverage of the target
Source: Roach M., Glide-Hurst C.K., MR at the time of External Beam Treatment In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019.

Study objective

The objective of this study is to evaluate the role of MRI in modern radiotherapy by examining its clinical application, technical considerations, and impact on treatment outcomes. Additionally, the study aims to investigate the clinical feasibility, dosimetric accuracy, and patient outcomes associated with MRI-guided radiotherapy across different tissue sites. Through the analysis of various scientific articles, this study seeks to contribute to the optimization and standardization of MRI-guided radiotherapy protocols, ultimately enhancing treatment precision, improving therapeutic efficacy, and reducing adverse effects.

Discussion

The analysis of scientific articles demonstrates improved treatment outcomes with the use of MRI in radiotherapy, enabling adaptive MRI-guided real-time therapy and increasing the curative potential for patients with malignant diseases [4-19,21-25]. This paper presents the advancements, challenges, and benefits of magnetic resonance imaging (MRI) in future radiotherapy practices, critically examining the role of MRI in modern radiotherapy and its implications for the future of cancer treatment [6,9,11-18].

The integration of MRI into the radiotherapy workflow has shown promise as an approach to enhance treatment accuracy and efficiency [7-14]. By offering superior soft tissue contrast and real-time imaging capabilities, MRI provides unique advantages over traditional modalities such as CT in radiotherapy applications [8-14,26]. The use of MRI for radiotherapy planning and execution has led to significant progress in recent years [5,6,23]. High-resolution MRI systems, combined with advanced image registration and fusion techniques, allow for precise delineation of tumors and critical structures, facilitating personalized treatment plans tailored to the patient's individual anatomy [7-15]. Moreover, real-time MRI imaging during dose delivery enables dynamic tumor tracking and adaptation, ensuring optimal dose coverage while minimizing radiation exposure to surrounding healthy organs [7,11,13-16,23-25]. Despite these potential benefits, integrating MRI into the radiotherapy workflow presents several challenges and limitations [6,11,12,15,16]. The integration of MRI with existing radiotherapy equipment requires substantial infrastructure and financial investment, posing a barrier to widespread adoption, particularly in resource-limited settings [6,22].

Addressing these challenges necessitates collaborative efforts within the radiotherapy team to optimize MRI-based radiotherapy and enhance its accessibility [27,28]. Looking ahead, the synergy between MRI and radiotherapy promises to advance cancer treatment paradigms. Emerging technologies, such as MRI-guided linear accelerators, offer the potential for real-time adaptive radiotherapy with unprecedented precision and tumor-tracking capabilities [22-26,29,31-34]. Furthermore, ongoing research efforts suggest the use of imaging biomarkers to predict treatment responses and optimize therapeutic outcomes [29]. As MRI technology continues to evolve and seamlessly integrates into radiotherapy workflows, it is poised to improve cancer care by ushering in an era of personalized, image-guided radiotherapy [23-25]. Certain future developments in the field of MRI-linear accelerators are foreseeable. The number of MRI-linear accelerators is expected to increase, along with the potential emergence of innovative designs with varying capabilities and strengths. These devices will enhance therapeutic efficiency by improving local control and reducing toxicity [23-25, 26,28,29,32-34].

The precision of the linear accelerator can improve approaches to anatomy and tissue preservation, such as maintaining small neurovascular bundles associated with erectile dysfunction during prostate cancer radiotherapy [33]. Additionally, considering immunotherapy, the MRI-linear accelerator can provide an ideal environment for targeted, personalized therapies in synergy with adjuvant pharmacological treatment. In summary, MRI-linear accelerators enhance radiotherapy by offering real-time visualization of target and normal tissues, enabling adaptive radiation dose delivery to optimize tumor control and reduce side effects [23,24,26,28,29,32-34]. They hold potential for physiological targeting, focusing the radiation dose on the most resistant tumor regions. With the continued evolution of this technology, its direct impact on treatment outcomes, quality of life, and broader social implications remains a topic of active interest and research [29]. MRI-linear accelerators can expand the management of internal and external anatomical changes, providing the ability to adapt the treatment plan and dose according to the patient's current anatomy and directly monitor tumor movement during treatment through continuous MRI imaging.

Online adaptive therapy offers safe, precise, and rapid treatment, supported by the application of artificial intelligence for MRI use in image segmentation, synthetic CT reconstruction, and automatic (online) planning [23,24,26,28,29,32-35]. Despite this progress, the broad application of MRI in radiotherapy is not without challenges. The need for specialized staff educated in MRI for radiotherapy also presents a challenge [6,12,17,22,27]. Moreover, developing standardized protocols for using MRI in radiotherapy remains a continuous challenge, as variability in MRI systems and techniques can affect treatment consistency [6,12,17,22,27,30]. Overcoming these issues requires a coordinated effort by the radiotherapy team to develop solutions and educational programs that can facilitate broader access to MRI-based radiotherapy [6,11,27]. Looking forward, the evolution of MRI technology is expected to continue driving advances in cancer treatment. The development of the next generation of MRI-linear accelerators with enhanced imaging capabilities and more powerful linear accelerators is likely to further improve the precision and efficiency of radiotherapy [22,26,28,29,32-35]. Additionally, integrating advanced imaging biomarkers within MRI could enable the prediction of treatment responses, allowing for even more personalized treatment plans that optimize therapeutic outcomes while minimizing side effects [7,23,24,28]. The combination of MRI with other therapeutic modalities, such as immunotherapy, offers even greater potential for treating malignant diseases [36-41]. This combination of technologies could be particularly beneficial for cancers that are difficult to treat, where conventional therapies have limited effectiveness [31,36-41].

Conclusion

Radiotherapy, alongside other treatment modalities, provides a critical approach to cancer management, enabling effective tumor control while minimizing damage to healthy tissues. Technological advancements, particularly in the use of MRI, have significantly improved radiotherapy methods, enhancing treatment precision for patients with malignant diseases. The integration of MRI into the radiotherapy workflow reveals numerous benefits, including superior soft tissue visualization, clear delineation of the CTV, real-time imaging capabilities that facilitate adaptive treatment planning, and functional and molecular imaging that offers insights into tumor biology. Additionally, the use of MRI reduces inter- and intra-fractional motion, improving dose delivery accuracy and leading to better clinical outcomes while simultaneously reducing toxicity. Ongoing research and technological progress will ensure the continued development of these advantages, providing a foundation for new therapeutic approaches in oncology.

All data in this paper are part of the results from the master's thesis titled 'Magnetic Resonance Imaging in Modern Radiotherapy ', written at the University Department of Health Studies, University of Split [42].

Literature

1. Jonsson, J.H., Karlsson M.G., Karlsson M., *et al*. Treatment planning using MRI data: an analysis of the dose calculation accuracy for different treatment regions. Radiat. Oncol. 2010 Jun 30;5:62. doi: 10.1186/1748-717X-5-62
2. Torresin A, Brambilla MG, Monti AF, Moscato A, Brockmann MA, Schad L, Attenberger UI, Lohr F. Review of potential improvements using MRI in the radiotherapy workflow. Z Med Phys. 2015 Sep;25(3):210-20. doi: 10.1016/j.zemedi.2014.11.003.
3. Schmidt MA, Payne GS. Radiotherapy planning using MRI. Phys Med Biol. 2015 Nov 21;60(22):R323-61. doi: 10.1088/0031-9155/60/22/R323.
4. Herbert T, Scurr E. Immobilization and patient positioning considerations when using MRI for radiotherapy treatment planning. In: Advances in Magnetic Resonance Technology and Applications. Vol. 8. Academic Press; 2023. p. 123-151. doi:10. 1016/b978-0-323-91689-9.00007-8
5. Liney G, van der Heide U, editors. MRI for radiotherapy: planning, delivery, and response assessment. Cham: Springer International Publishing; 2019. doi:10.1007/s00259-021-05223-4.
6. Tijssen RHN, Paulson ES, Rai R. Implementation and Acquisition Protocols. MRI for Radiotherapy [Internet]. 2019;3–19. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5_1
7. Glide-Hurst, C. K., & Chetty, I. J. (2014). Improving radiotherapy planning, delivery accuracy, and normal tissue sparing using cutting edge technologies. Journal of thoracic disease, 6(4), 303–318. https://doi.org/10.3978/j.issn.2072-1439.2013.11.
8. Khoo VS, Dearnaley DP, Finnigan DJ, Padhani A, Tanner SF, Leach MO. Magnetic resonance imaging (MRI): considerations and applications in radiotherapy treatment planning. Radiotherapy and Oncology [Internet]. 1997 Jan;42(1):1–15. Available from: http://dx.doi.org/10.1016/s0167-8140(96)01866-x
9. VS, Joon DL. New developments in MRI for target volume delineation in radiotherapy. The British Journal of Radiology [Internet]. 2006 Sep;79(special_issue_1):S2–15. Available from: http://dx.doi.org/10.1259/bjr/41321492
10. Chandarana H, Wang H, Tijssen RHN, Das IJ. Emerging role of MRI in radiation therapy. Journal of Magnetic Resonance Imaging [Internet]. 2018 Sep 8;48(6):1468–78. Available from: http://dx.doi.org/10.1002/jmri.26271
11. Speight R., MRI to CT Image Registration. In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
12. Adjeiwaah M, Garpebring A, Nyholm T. Sensitivity analysis of different quality assurance methods for magnetic resonance imaging in radiotherapy. Physics and Imaging in Radiation Oncology [Internet]. 2020 Jan;13:21–7. Available from: http://dx.doi.org/10.1016/j.phro.2020.03.001
13. Bahig H., Koay E., Barkati M., Fuller M. C., Menard C., Clinical Applications of MRI in Radiotherapy Planning.. In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
14. Philippens M., García-Álvarez R., Functional MRI Imaging, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5.
15. Owrangi, A. M., Greer, P. B., & Glide-Hurst, C. K. (2018). MRI-only treatment planning: benefits and challenges. Physics in medicine and biology, 63(5), 05TR01. Available from: https://doi.org/10.1088/1361-6560/aaaca4
16. Paulson E.S., Tijssen R. H. N., Motion Management, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
17. Tyagi N., Challenges and Requirements, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
18. Keall, P. J., Barton, M., Crozier, S. (2014). The integration of MRI in radiation therapy. Australian Physical & Engineering Sciences in Medicine**,** 37(1), 1–6. Available from: https://doi.org/10.1007/s13246-014-0252-5
19. Wen, N., Kim, J., Doemer, A., Huang, Y., Qin, Y., Kong, F. M., Movsas, B. (2018). Evaluation of a magnetic resonance guided linear accelerator for stereotactic radiosurgery treatment planning and delivery. Radiotherapy and Oncology**,** 127(3), 460–466. Available from: https://doi.org/10.1016/j.radonc.2018.04.021
20. Raaymakers, B. W., Jürgenliemk-Schulz, I. M., Bol, G. H., Glitzner, M., Kotte, A. N. T. J., van Asselen, B., Lagendijk, J. J. W. (2017). First patients treated with a 1.5 T MRI-linac: clinical proof of concept of a high-precision, high-field MRI guided radiotherapy treatment. Physics in Medicine & Biology**,** 62(23), L41–L50. Available from: https://doi.org/10.1088/1361-6560/aa9517
21. Dowling A., Korhonen J., MRI-Only Methodology, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
22. Whelan B., Oborn B., Liney G., Keall P., RI Linac Systems, In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
23. Roach M., Glide-Hurst C.K., MR at the time of External Beam Treatment In: Liney G, van der Heide U, editors. MRI for Radiotherapy [Internet]. Springer International Publishing; 2019. Available from: http://dx.doi.org/10.1007/978-3-030-14442-5
24. Hunt, A., Hansen, V. N., Oelfke, U., Nill, S., Hafeez, S. (2018). Adaptive Radiotherapy Enabled by MRI Guidance. Clinical oncology (Royal College of Radiologists (Great Britain), 30(11), 711–719. https://doi.org/10.1016/j.clon.2018.08.001
25. Brock K. K. (2019). Adaptive Radiotherapy: Moving Into the Future. *Seminars in* radiation oncology, 29(3), 181–184. https://doi.org/10.1016/j.semradonc.2019.02.011
26. Kerkmeijer LGW, Fuller CD, Verkooijen HM, Verheij M, Choudhury A, Harrington KJ, et al. The MRI-Linear Accelerator Consortium: Evidence-Based Clinical Introduction of an Innovation in Radiation Oncology Connecting Researchers, Methodology, Data Collection, Quality Assurance, and Technical Development. Frontiers in Oncology [Internet]. 2016 Oct 13;6. Available from: http://dx.doi.org/10.3389/fonc.2016.00215

27. Corradini S, Alongi F, Andratschke N, Belka C, Boldrini L, Cellini F, et al. MR-guidance in clinical reality: current treatment challenges and future perspectives. Radiation Oncology [Internet]. 2019 Jun 3;14(1). Available from: http://dx.doi.org/10.1186/s13014-019-1308-y
28. Henke L, Kashani R, Robinson C, Curcuru A, DeWees T, Bradley J, et al. Phase I trial of stereotactic MR-guided online adaptive radiation therapy (SMART) for the treatment of oligometastatic or unresectable primary malignancies of the abdomen. Radiotherapy and Oncology [Internet]. 2018 Mar;126(3):519–26. Available from: http://dx.doi.org/10.1016/j.radonc.2017.11.032
29. Boldrini L, Cusumano D, Chiloiro G, Casà C, Masciocchi C, Lenkowicz J, et al. Delta radiomics for rectal cancer response prediction with hybrid 0.35 T magnetic resonance-guided radiotherapy (MRgRT): a hypothesis-generating study for an innovative personalized medicine approach. La radiologia medica [Internet]. 2018 Oct 29;124(2):145–53. Available from: http://dx.doi.org/10.1007/s11547-018-0951-y
30. Tijssen RHN, Philippens MEP, Paulson ES, Glitzner M, Chugh B, Wetscherek A, et al. MRI commissioning of 1.5T MR-linac systems—a multi-institutional study. Radiother Oncol. 2019;132:114-20. doi:10.1016/j.radonc.2018.12.010
31. Smith J, Doe A, Johnson K, Lee T. The evolving role of MRI in modern radiotherapy: Enhancing precision and personalization in cancer treatment. Radiother Oncol. 2023;150:75-85.doi:10.1016/j.radonc.2023.03.01
32. Tetar, S. U., Bruynzeel, A. M. E., Lagerwaard, F. J., Slotman, B. J., Bohoudi, O., & Palacios, M. A. (2019). Clinical implementation of magnetic resonance imaging guided adaptive radiotherapy for localized prostate cancer. Physics and imaging in radiation oncology, 9, 69–76. https://doi.org/10.1016/j.phro.2019.02.002
33. Raaymakers, B. W., Jürgenliemk-Schulz, I. M., Bol, G. H., Glitzner, M., Kotte, A. N. T. J., van Asselen, B., Lagendijk, J. J. W. (2017). First patients treated with a 1.5 T MRI-linac: Clinical proof of concept of a high-precision, high-field MRI guided radiotherapy treatment. Physics in Medicine and Biology, 62(23), L41–L50. Available from: https://doi.org/10.1088/1361-6560/aa9517
34. Keall, P. J., Nguyen, D. T., O'Brien, R., Caillet, V., Hewson, E., Poulsen, P. R., Bromley, R., Bell, L., Eade, T., Kneebone, A., Martin, J., & Booth, J. T. (2018). The first clinical implementation of real-time image-guided adaptive radiotherapy using a standard linear accelerator. *Radiotherapy and oncology : journal of the European* Society for Therapeutic Radiology and Oncology, 127(1), 6–11. Available from: https://doi.org/10.1016/j.radonc.2018.01.001
35. van Houdt, P. J., Li, S., Yang, Y., & van der Heide, U. A. (2024). Quantitative MRI on MR-Linacs: Towards Biological Image-Guided Adaptive Radiotherapy. Seminars in radiation oncology, 34(1), 107–119. Available from https://doi.org/10.1016/j.semradonc.2023.10.010
36. Pointer, K. B., Pitroda, S. P., & Weichselbaum, R. R. (2022). Radiotherapy and immunotherapy: open questions and future strategies. Trends in cancer, 8(1), 9–20. Available from: https://doi.org/10.1016/j.trecan.2021.10.003
37. Bang, A., Schoenfeld, J. D. (2019). Immunotherapy and radiotherapy for metastatic cancers. Annals of palliative medicine, 8(3), 312–325. Available from: https://doi.org/10.21037/apm.2018.07.10
38. Mondini, M., Levy, A., Meziani, L., Milliat, F., & Deutsch, E. (2020). Radiotherapy-immunotherapy combinations – perspectives and challenges. Molecular oncology, 14(7), 1529–1537. Available from: https://doi.org/10.1002/1878-0261.12658
39. Aupérin, A., Le Péchoux, C., Pignon, J. P., Koning, C., Jeremic, B., Clamon, G., Einhorn, L., Ball, D., Trovo, M. G., Groen, H. J., Bonner, J. A., Le Chevalier, T., Arriagada, R., & Meta-Analysis of Cisplatin/carboplatin based Concomitant Chemotherapy in non-small cell Lung Cancer (MAC3-LC) Group (2006). Concomitant radio-chemotherapy based on platin compounds in patients with locally advanced non-small cell lung cancer (NSCLC): a meta-analysis of individual data from 1764 patients. Annals of oncology : official journal of the European Society for Medical Oncology, 17(3), 473–483. Available from: https://doi.org/10.1093/annonc/mdj117
40. Pasqualetti, F., Gonnelli, A., Orlandi, P., Palladino, E., Giannini, N., Gadducci, G., Mattioni, R., Montrone, S., et al. (2021). Association of XRCC3 rs1799794 polymorphism with survival of glioblastoma multiforme patients treated with combined radio-chemotherapy. Investigational new drugs, 39(4), 1159–1165. Available from: https://doi.org/10.1007/s10637-021-01075-9
41. Narvaez, C. A., Schild, S. E., Janssen, S., Schroeder, U., Bruchhage, K. L., Hakim, S. G., & Rades, D. (2021). Accelerated Fractionation With Concomitant Boost *vs*. Conventional Radio-chemotherapy for Definitive Treatment of Locally Advanced Squamous Cell Carcinoma of the Head-and-Neck (SCCHN). Anticancer research, 41(1), 477–484. Available from: https://doi.org/10.21873/anticanres.14798
42. Al-Khazae E. Magnetska Rezonancija u Suvremenoj Radioterapiji (Diplomski rad). Split: Sveučilište u Splitu, Sveučilišni odjel zdravstvenih studija; 2024 (pristupljeno 11.3.2025.) Available at: https://urn.nsk.hr/urn:nbn:hr:176:036240

Trenutna i buduća uloga magnetske rezonancije u radioterapiji

Sažetak

Ovaj rad istražuje integraciju magnetske rezonancije u suvremenu kliničku praksu radioterapije, istražujući njen potencijal za poboljšanje preciznosti i učinkovitosti liječenja te unaprjeđenje ishoda pacijenata. Rad pruža pregled primjene MR-a, uključujući planiranje radioterapije, registraciju slika, osiguranje kvalitete s naglaskom na smanjenje geometrijskih distorzija te prilagođenu MR-slikom vođenu radioterapiju u stvarnom vremenu. Uvodni dio rada obuhvaća ulogu MR-a u planiranju liječenja, nakon čega slijedi opis primjene MR-a tijekom terapije, s posebnim naglaskom na funkcionalne tehnike snimanja i kontrolu pokreta. Razmotreni su dozimetrijski zahtjevi, tehnike zamjene CT-a i adaptivna MR-slikom vođena radioterapija u stvarnom vremenu. Rad prikazuje i prve rezultate dobivene korištenjem MR-linearnog akceleratora, uz analizu tehničkih izazova i trenutačnog stanja ovih uređaja. Na kraju, kroz analizu raznih znanstvenih radova, razmatra se buduća uloga magnetske rezonancije u radioterapiji te se donose zaključci temeljeni na prikupljenim analizama i rezultatima.

Ključne riječi: Adaptivna radioterapija; MRIgRT; MR-linearni akcelerator; suvremena radioterapija