sciendo
Polish Journal of Medical Physics and Engineering
The Journal of Polish Society of Medical Physics
ISSN 1898-0309, doi: 10.2478/pjmpe-2025-0020
September 2025
Vol 31, Issue 3

Review paper

Adaptive radiation therapy in practice: classification and technical insights from Polish Society of Medical Physics experts

Tomasz Piotrowski [1,2,3,ABCDF,*], Anna Zawadzka [4,CEF], Janusz Winiecki [5,6,CEF], Marcin Dybek [7,EF], Agnieszka Skrobała [1,2,CEF]

[1]*Department of Electroradiology, Poznan University of Medical Sciences, Poznan, Poland*
[2]*Department of Medical Physics, Greater Poland Cancer Centre, Poznan, Poland*
[3]*Department of Biomedical Physics, Adam Mickiewicz University in Poznan, Poznan, Poland*
[4]*Department of Medical Physics. Maria Skłodowska Curie Memorial Cancer Centre and Institute of Oncology in Warsaw, Warszawa, Poland*
[5]*Department of Medical Physics, Oncology Centre, Bydgoszcz, Poland*
[6]*Department of Oncology and Brachytherapy, Nicolaus Copernicus University, Torun, Poland*
[7]*Department of Radiotherapy, Katowice Oncology Centre, Katowice, Poland*
**Corresponding author: Tomasz Piotrowski, tomasz.piotrowski@me.com*

(received: 29 April 2025; accepted 1 July 2025)

Abstract

This educational review provides a comprehensive overview of adaptive radiation therapy (ART), an advanced approach to adjusting radiotherapy plans in response to anatomical or physiological changes during treatment. It classifies ART into three methods, i.e. offline, online, and real-time, distinguished by the timing of plan modifications relative to the treatment session. The review emphasises the importance of monitoring discrepancies between planned and delivered doses through advanced imaging and dose-tracking techniques, and how timely adaptation can exploit this information to maintain target coverage and minimise unnecessary exposure of healthy tissues. Key enabling technologies are discussed, including high-quality on-board imaging modalities (CT, cone-beam CT, MRI, PET) for accurate visualisation of current anatomy, deformable image registration and automated contour propagation for efficient mapping of anatomical changes, and reliable dose recalculation on images from the treatment machine to ensure dosimetric accuracy of adapted plans. Equally important, rigorous quality assurance (QA) protocols are outlined, including validation of image registration accuracy (to verify deformable alignment), end-to-end testing of the entire adaptive workflow, patient-specific plan verification via independent dose checks or in vivo dosimetry, and thorough risk analysis (such as failure mode and effects analysis) to anticipate potential errors. Clear adaptation criteria and multidisciplinary team oversight are recommended to ensure that adaptive interventions fulfil the promise of improved tumour control and reduced toxicity without compromising patient safety.

Keywords: adaptive radiation therapy, offline adaptation, online adaptation, real-time adaptation

Rationale for developing adaptive radiotherapy methods

One of the key steps in preparing a patient for radiotherapy is treatment planning. Treatment plans are developed using a computer environment equipped with specialised software that enables the design, simulation, and verification of dose distributions. To individualise therapy, dose distributions are presented on CT scans acquired before treatment initiation in the treatment position, depicting the region's anatomy where the tumour and organs at risk are located. The treatment plan is created such that: (1) the dose distribution metrics meet the guidelines specified by the radiation oncologist, (2) the complexity of plan delivery on the treatment machine is minimised, and (3) the plan is robust against factors that could cause discrepancies between the planned dose and the dose delivered to the target area during treatment[1]. Nevertheless, the discrepancies between the planned and delivered doses may be greater than anticipated during treatment planning. These discrepancies result primarily from anatomical variability of the irradiated area due to physiological processes. Moreover, during the execution of radiation delivery, which is a fractionated process, there is a possibility of variations in patient positioning. The so-called inter-fraction patient setup error on the treatment table and changes in the relative positions of the tumour and organs at risk influence variations in the dose distribution recorded during each session of a multi-week radiotherapy course.

© 2025 Authors
This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivs License (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Authors' contribution:
A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

Modern imaging technologies used in radiotherapy (IGRT – *image-guided radiation therapy*) allow assessment of the geometric discrepancy between the patient's anatomy on which the treatment plan was based and its current shape during therapy. However, using IGRT procedures alone, one cannot unambiguously determine the impact of anatomical changes on the dose distribution in the patient's body, nor evaluate how the current anatomy aligns with the target volume and organs at risk. Moreover, in most cases, IGRT procedures only allow corrective action when the discrepancy between planned and current anatomical conditions is significant and noticeable[2]. Nevertheless, advances in imaging, increased computational power, and improved algorithms have enabled the calculation of dose distributions delivered during each treatment fraction and their direct display on images acquired from the treatment unit. Fractional dose monitoring and its evaluation against the planned doses, known as DGRT (*dose-guided radiation therapy*), has become another powerful tool for quantitative assessment of treatment delivery quality[3,4]. Information obtained through IGRT and DGRT procedures provides the basis for assessing the accuracy of treatment plan execution. A discrepancy between the original treatment plan and its current delivery on the treatment machine, as detected via IGRT/DGRT procedures, could be a rationale for modifying the plan so that the adapted plan meets the initial assumptions and clinical criteria established before therapy. Modifying the treatment plan during the radiotherapy course is termed ***plan adaptation***, and radiotherapy during which information on treatment accuracy is gathered and used to modify the plan, is termed ***adaptive radiotherapy*** (ART).

Goals and classification of ART methods

The main goal of ART is to monitor the consistency between the planned and delivered doses and to implement corrective procedures (plan adaptation) if the discrepancy between these doses becomes significant[5]. Numerous factors can cause a mismatch between planned and delivered doses. These changes occur across different time scales – from seconds or minutes (e.g. respiratory motion) to days or weeks (e.g. tumour volume changes). Depending on the time scale of these changes, three primary classes of ART are distinguished (**Figure 1**)[5]:

- **Offline** – adaptation between irradiation fractions, i.e. a plan modification performed after completing the *n*-th fraction in which significant discrepancies between the planned and delivered dose were observed. The modified plan is implemented at the next fraction (*n*+1) of irradiation.
- **Online** – adaptation is performed just before a treatment fraction, based on information about the patient's anatomy collected immediately prior to delivering that fractional dose.
- **Real-time** – adaptation in real time, i.e. during the delivery of the fractional dose, where the current position of the irradiated volume is determined from imaging data acquired

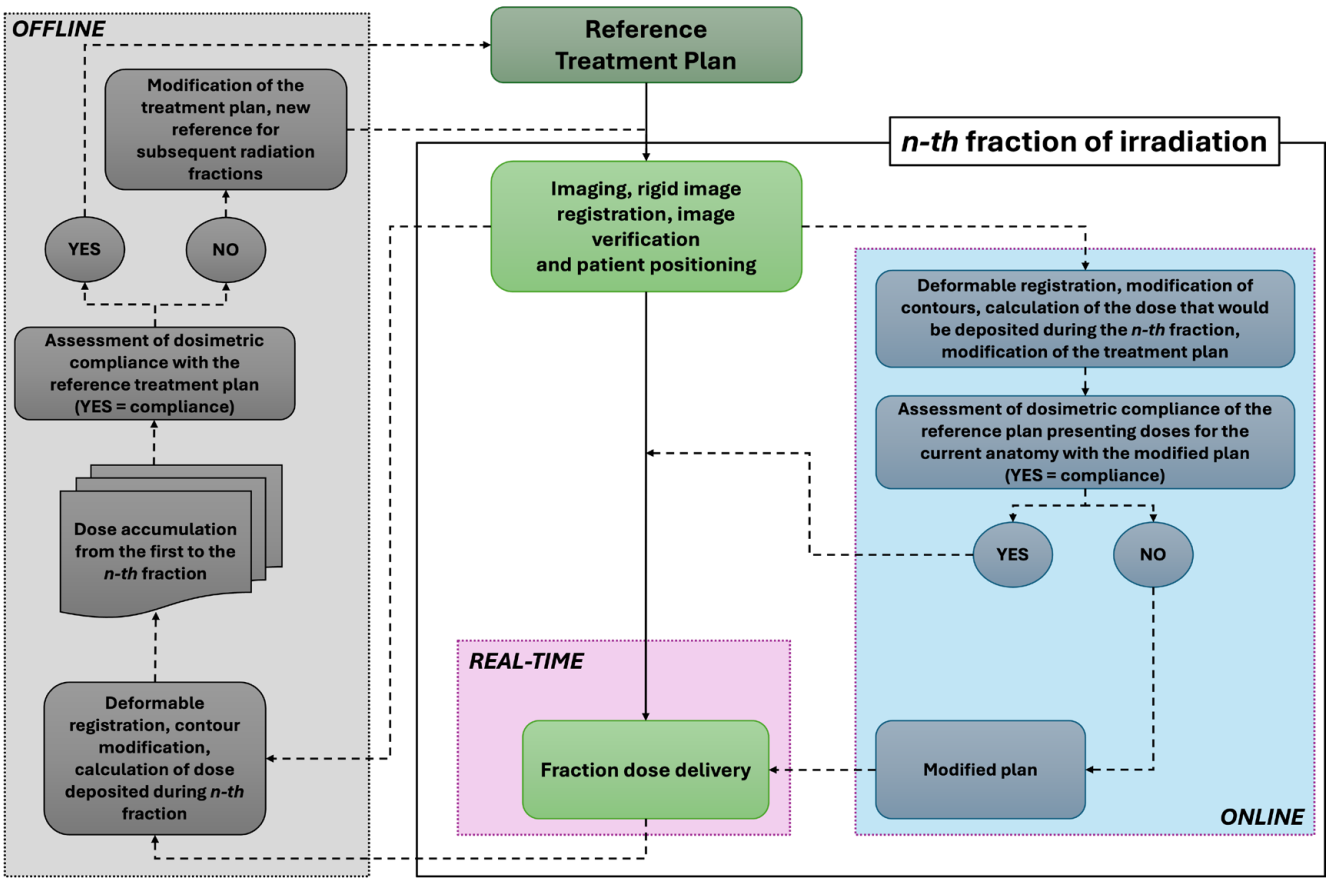


Figure 1. Conventional radiotherapy workflow (green) with the inclusion of adaptive radiotherapy methods: offline (grey), online (blue), and real-time (pink).

intra-fractionally and, if necessary, beam delivery parameters are modified on the fly.

The **offline** method is used for patients in whom progressive anatomical changes occur in the irradiated area over the course of radiotherapy. Progressive changes are characterised as directional, gradual, and systematic, with slow dynamics, manifesting over days to weeks[6]. These changes may result, for example, from weight loss, changes in the shape of the treatment area, or displacement of organs at risk due to tumour shrinkage. Once significant discrepancies are found between the planned and delivered doses, a common approach is to perform an additional planning session (the classical scheme) to modify treatment. This involves: (1) repeat imaging using a diagnostic CT scanner, (2) re-delineation of anatomical structures and tumour, and (3) new treatment plan optimisation with dosimetric verification.[7] However, modern radiotherapy technologies allow substantial simplification and automation of this procedure by using a contemporary adaptive workflow, in which[7]:

1. Instead of acquiring a new diagnostic CT scan, volumetric images acquired on the treatment machine (on-board imaging) can be used.
2. Instead of contouring new anatomical structures from scratch, existing contours from the reference plan can be utilised. To do this, the reference plan CT is deformably registered with the images acquired on the treatment unit, and the resulting deformation is applied to modify the reference contours. These adjusted contours are thus fitted to the current anatomy visible on the on-board images. This contour propagation procedure is fully automated; however, it still requires verification and possible minor corrections by the radiation oncologist (no need to re-contour all structures manually).
3. Instead of performing an entirely new plan optimisation, the optimisation constraints or results from the reference plan can serve as a starting point for re-optimisation, adjusting the plan to reduce dose distribution discrepancies caused by patient anatomy changes.

It is, of course, possible to combine classical and contemporary approaches — for instance, by applying contemporary contour mapping techniques to images obtained from a diagnostic CT scanner.

The **offline** method (particularly the classical scheme) can be implemented on all medical linacs currently in use. However, if the anatomical changes are not progressive (i.e. they are random or non-directional) and occur on shorter time scales (day-to-day changes or sudden differences just before dose delivery), the offline approach becomes inefficient. In such cases, after analysing the updated anatomical information and estimating the predicted dose distribution, it is necessary to implement corrective actions (plan adaptation) prior to delivering the fractional dose, rather than waiting to adapt at the next fraction as with offline methods. An adaptation procedure performed just before delivering a fraction is called **online** adaptive radiotherapy[8]. In online adaptation, plan modification cannot follow the classical offline workflow (new diagnostic CT and subsequent steps as in the classical scheme); instead, the contemporary adaptive workflow is used, with the crucial distinction that it must be carried out under time pressure while the patient is on the treatment table waiting for irradiation. Therefore, for online procedures, a well-optimised workflow and coordination of the team responsible for adaptation are critical[9]. Currently, in 2025, online adaptive radiotherapy is clinically available on selected accelerators: for example, Varian Ethos (Siemens Healthineers), Unity and EVO from Elekta, and Accuray Radixact. (*Note: Due to the certification process, Accuray solutions will be available in late 2025 or early 2026.*)

In contrast to offline and online methods, **real-time** ART refers to adaptation during actual dose delivery, i.e. modifying beam parameters intra-fractionally without operator intervention, in response to dynamic changes in the target volume position (in most cases, tumour motion). These changes are driven by respiratory motion, peristalsis, or other internal organ motion, and are detected from medical imaging acquired during irradiation (this is essential for a method to qualify as real-time adaptation)[5,10]. There are two main variants of real-time adaptation: (1) dynamic tumour tracking performed by the treatment system, available on Accuray devices (CyberKnife and Radixact), and (2) physiological gating (e.g. based on respiration or cardiac pulsation) using 4D-MR image sequences acquired during irradiation, available on the Elekta Unity machine and the ViewRay MRIdian system. *(Note: In mid-2023, ViewRay, the manufacturer of MRIdian, declared bankruptcy, though its products continue to be used.)*

Technologies enabling the ART implementation

Imaging. Tomograms acquired on a diagnostic CT scanner before the start of radiotherapy are the primary source of information about patient anatomy and are used in the treatment planning process. The success of radiotherapy is directly related to the accuracy of dose delivery to the patient's body according to the treatment plan. Images acquired directly on the treatment unit assess the geometric agreement between the anatomy used for treatment planning and the anatomy present during irradiation. These include planar images acquired with the treatment beam (2D-MV), X-rays (2D-kV), and volumetric images. Developments in on-board imaging technology on treatment machines have significantly improved the quality of volumetric images, which have become widely used for image-guided radiotherapy (IGRT). Currently, rigid registration of the planning CT with images acquired on the treatment unit before each fraction is the main tool for patient positioning on the treatment table. The registration results can also be used to qualitatively analyse individual anatomical structures (e.g., organs at risk, blocks of soft tissues, target volume), their current location, shape, and volume[11].

The most used volumetric on-board images are: (1) cone-beam computed tomography (CBCT) – a solution widely available on most modern linacs[12,13], and (2) mega-voltage

(MVCT) or kilo-voltage (kVCT) fan-beam helical CT, a solution typically used in tomotherapy systems (Accuray's TomoTherapy and Radixact platforms)[14,15]. It should be noted that other imaging modalities, such as MRI and PET, are also employed in clinical practice[16-18]. In certain clinical scenarios, these modalities significantly enhance the anatomical and functional information about the patient. MR imaging on a treatment unit is currently possible with systems like Elekta's Unity or ViewRay MR-linacs, and hybrid PET/CT imaging is available with the Reflexion X1 system by RefleXion (*Note: to date, only one clinical installation, as of 2025*). PET images are gaining popularity in radiotherapy. These images are used not only during the treatment planning stage (before the start of treatment) but also throughout the treatment to monitor the biological response to therapy[17]. This type of imaging during radiotherapy opens a broad field of clinical research into dynamically modifying dose delivery schemes during treatment depending on the tumour's response to irradiation. This concept is known as biologically guided radiation therapy (BgRT) and lays the groundwork for a new biologically driven form of adaptation[19]. It is difficult to predict whether biological adaptation will be implemented offline or online; however, the progressive nature of biological changes monitored via PET suggests that this method will likely fall under offline adaptation. In the context of biological monitoring during radiotherapy, one must also mention the functional MR imaging capabilities enabled by technologies available on Elekta Unity MR-linac[20]. The Unity system can also acquire 4D-MR image sequences during a treatment fraction[21]. These intrafraction 4D-MR images form the basis of one variant of real-time adaptation - **physiological gating,** called comprehensive motion management (CMM)[5]. The second variant of real-time adaptation is dynamic tumour tracking, where the treatment system adjusts in real-time on ultra-fast analysis of 2D-kV planar images acquired during dose delivery, a feature available on systems such as Accuray's CyberKnife and Radixact[22].

Dose calculation. A key issue for effective use of on-board volumetric images in offline and online adaptation is the ability to use those images for dose calculation. These calculations should be as accurate as those performed on conventional diagnostic CT images. The main factor causing discrepancies between dose calculations on diagnostic CT vs. tomograms from treatment machines is the difference in the proportion of primary vs. scattered radiation collected during imaging, which is used as raw data for reconstructing the image[23]. Primary radiation (and its attenuation information through the imaged object) is the main signal used in CT image reconstruction. In contrast, scattered radiation is a source of inaccuracy and should be effectively minimised. In conventional diagnostic CT scanners, scatter is minimised mechanically (through detector design) and algorithmically (during image reconstruction). Unfortunately, for images from treatment machines, scattering because of the design limitations of the on-board imaging systems is only reduced during the image reconstruction process. This results in images with distorted Hounsfield unit (HU) values and, consequently, incorrect conversion to electron or mass densities, whose accuracy directly affects the precision of dose calculation. This applies mainly to linacs where images are acquired via CBCT. An exception is MVCT images from tomotherapy units (TomoTherapy, Radixact), which use a gas detector design like third-generation diagnostic CT detectors[14]. It is worth noting that some newer linacs feature reconstruction algorithms that significantly reduce scatter, resulting in CBCT-based dose calculations that are approaching the accuracy of those performed on diagnostic CT scans[24].

If the on-board images do not guarantee dose calculation accuracy comparable to diagnostic CT, advanced image data management techniques can be employed to enable dose computation on a synthetic CT image (sCT)[25]. To create an sCT, a deformable registration is performed between the on-board images and the reference CT from planning, and the resulting deformation vector field is applied to warp the reference CT, mapping the current anatomy onto it. The sCT generated this way is then used for dose calculation[25]. The sCT generation procedure is also utilised when the on-board images are from modalities not directly intended for dose calculation (e.g. MR images)[26]. In such cases, the MR images can be deformably registered to the planning CT or combined with other techniques (such as machine learning models) to produce a synthetic CT for dose computation[27]. This approach ensures that dose calculations reflect the current anatomy using a medium (CT Hounsfield units) suitable for accurate dose computation.

Image and dose data management. Given the dynamic anatomical changes during treatment, monitoring the correctness of a radiotherapy course requires advanced methods of managing imaging data and dose information. Proper interpretation of dose distributions calculated directly on on-board images or indirectly on sCTs requires not only well-implemented deformable image registration methods, but also that the mapping of anatomical changes can be used to efficiently transform structure contours from the reference plan to match the current patient anatomy[28]. Both deformable image registration and automatic contour adaptation are automated processes; thus, they must be validated. For deformable registration, validation should be quantitative (evaluating metrics derived from the deformation vector field, DVF) and qualitative, e.g. visual inspection of deformed image overlays[29]. Another issue requiring validation is using artificial intelligence (AI) for contouring. AI-based auto-contouring tools are becoming increasingly widespread throughout radiotherapy, not only in adaptive applications, and their quality continues to improve. However, an important aspect is evaluating these tools concerning the limitations of the model's performance. Regardless of the auto-contouring method, a radiation oncologist must review, approve, and, if necessary, manually adjust the automatic contour modifications to ensure clinical accuracy[30]. Proper execution of these automated procedures (deformable registration and contour propagation) allows recreation of the patient's current anatomy and thus calculation of the dose distribution that would be delivered by the reference treatment plan to that anatomy. Consequently, one can evaluate the impact of anatomical changes on the doses delivered to

the target and organs at risk. If anatomy changes significantly or adversely affects the dose distribution in the target or organs at risk, one may decide to modify the original treatment plan. The above scenario corresponds to offline ART procedures[7]. Due to time constraints in online ART, the dose distributions that would result from delivering the reference plan and the dose distributions from an automatically generated adapted plan are presented simultaneously[7]. The physician or physicist can then evaluate the potential benefit of using the adapted plan and decide whether to proceed with the new plan or continue treatment with the original plan.

Another key element is managing the dose information accumulated throughout the radiotherapy course. Due to inter-fraction anatomical variability of the treated area, there is a justified need to monitor the volumes of irradiated structures and the doses delivered to them in each fraction. To correctly present cumulative dose increments over the treatment course, a reverse deformable dose mapping registration procedure should be applied: the DVFs are used to deform the dose distribution computed on each day's on-board images back onto the reference planning CT, where doses from each fraction can be successively accumulated. In contrast to the previously described procedure (where images and contours are deformed and dose is calculated afterwards), here the pre-calculated dose distributions are warped to align with the reference anatomy and then summed over fractions. The accuracy of this cumulative dose tracking depends directly on the accuracy of the DVF, i.e. on the quality of the image registration method implemented[31,32]. By tracking dose accumulation over successive fractions, one can analyse cumulative dose trends and their consistency with the intended dose escalation strategy established in the reference plan[32].

Quality assurance (QA) of ART methods

The implementation of adaptive radiotherapy significantly increases the complexity of the treatment process. New potential sources of error emerge, from incorrect image deformation or contour propagation to the risk of mistakes due to the frequent generation and use of the modified treatment plans. Moreover, in online adaptive radiotherapy, errors in delineating target volumes for each fraction, combined with time pressure and the absence of independent audits, may introduce additional inaccuracies that require evaluation. Therefore, ART's quality assurance (QA) must be comprehensive and rigorous. It encompasses traditional elements (accelerator calibration, dose verification) and novel components such as validation of deformable registration algorithms, end-to-end testing of the entire adaptive process, and more. Below is an outline of the key QA elements involved in adaptive radiotherapy workflows.

Offline and online methods: validation of deformable registration and contour propagation. AAPM Task Group 132 provides guidelines for assessing image registrations' quality[29]. These include, among others, visual tests (such as image overlay, examination of DVF vector maps with highlighting of suspicious non-anatomical deformations) and the use of dedicated registration phantom datasets. In practice, testing the deformable registration algorithm on known cases before deploying adaptive radiotherapy is recommended – for example, using the digital phantom and reference image data sets provided by TG-132[29]. Automated contour propagation should likewise be evaluated by comparing propagated structures to known ground truth datasets and ensuring clinicians review all automatically adjusted contours before use.

Offline, online, and real-time methods: QA of imaging systems. In addition to standard accelerator quality assurance (per recommendations such as AAPM TG-142[33]), the scope of QA must be expanded to cover the imaging system. This includes verifying the geometric accuracy and the image quality of on-board imaging used for offline/online adaptation (MVCT, kVCT, CBCT, MR images) and real-time adaptation (2D kV planar images and 4D-MR sequences). It is also necessary to verify the accurate transfer and interpretation of imaging data between different components of the treatment workflow, ensuring that images acquired on the treatment unit are correctly interpreted by the planning system (with proper image orientation, scale, and Hounsfield unit calibration). Moreover, it should be noted that, unlike treatment units without MR imaging, MR-linacs require specialised dosimetry protocols to account for the influence of the magnetic field on detector response during dose measurements[34].

Offline, online, and real-time methods: end-to-end testing and risk analysis. The complexity of adaptive radiotherapy means that separately validating the deformable registration, the planning process, or the accelerator performance might not catch issues at their interfaces. It is therefore advisable to conduct a comprehensive **end-to-end test** of the entire adaptation procedure before full clinical implementation, and thereafter to repeat these tests on a schedule and after any process modifications[35]. Such a test involves simulating and evaluating the complete adaptive treatment scenario on a phantom – from imaging, through adaptive plan preparation, to delivery and dose measurement. Additionally, performing a process risk analysis (FMEA – *Failure Mode and Effects Analysis*) for the entire ART workflow is highly beneficial. This analysis helps identify potential critical failure points (e.g. "What if the deformable registration fails?" or "What if the planning system generates a plan incompatible with the machine specifications?") and to prepare contingency or additional control procedures. Nishioka *et al.* and Wegener *et al.* have published FMEA analyses for real-time and online adaptation, which can guide the development of local QA protocols[36,37].

Offline and online methods: patient-specific QA of adaptive plans. Each new radiotherapy plan should undergo dosimetric verification (i.e., patient-specific QA, PSQA). In offline adaptation, the modified plan can be verified using standard measurement-based QA methods by evaluating agreement with planned values. In online adaptation, the plan is modified just before irradiation, with the patient on the table, so performing a traditional PSQA measurement is often not feasible. Therefore, one commonly used, simplified PSQA meth-

od is to perform a secondary dose calculation of the modified plan using an independent system[38]. Another approach is *in vivo* monitoring using transit dosimetry methods[39] and analysis of delivered dose distributions after each fraction by examining the treatment delivery log files generated by the machine during irradiation[40]. However, the latter method is less popular because any information about potential issues with the adapted plan is available only after delivery. Regardless of the QA method adopted, adaptive (modified) plans must meet the same acceptance criteria as the original reference plans created before the start of radiotherapy.

Offline and online methods: adaptation criteria and clinical oversight. Although not a classic "physics/technical QA" element, clear guidelines for when and how to adapt are critically important. Establishing well-defined action levels for plan adaptation prevents arbitrary decisions and disorganisation in the adaptive process. The entire process requires oversight and involvement of an experienced multidisciplinary team: the attending radiation oncologist, medical physicist, and radiation technologists must work together to ensure that each adaptation is performed according to protocol and properly documented. Clearly defining the responsibilities of each group involved in the process for the individual stages of the procedure also appears to be an essential element. This clinical supervision helps maintain consistency and safety when implementing adaptive therapy[9].

Conclusion

Adaptive radiation therapy (ART) represents a significant advancement in precision radiotherapy, enabling treatment plans to be adjusted in response to anatomical or physiological changes during the treatment course. This review has outlined the three principal categories of ART, i.e. offline, online, and real-time adaptation, which are defined by the timing and immediacy of plan modifications. Key messages include the importance of monitoring discrepancies between planned and delivered doses, leveraging image guidance (IGRT) and dose tracking (DGRT) to trigger plan adaptations, and the potential of emerging technologies like MR-guidance and PET-guidance to further personalise therapy. Technological considerations for successful ART implementation encompass high-quality on-board imaging (CT, CBCT, MRI, PET) for accurate anatomy visualisation, robust deformable image registration and automated contour propagation algorithms, and reliable dose calculation on non-conventional images (using techniques like synthetic CT generation) to maintain dosimetric accuracy. The integration of these technologies, combined with enhanced computing power and automation, now allows clinics to routinely recalculate doses on the fly and compare adaptive plans within the limited time between or even during treatment sessions.

Clinically, adaptive radiotherapy offers the promise of improved target coverage and normal tissue sparing by accounting for tumour shrinkage, patient weight loss, organ motion, or other changes that occur over a multi-week treatment regimen. However, translating this promise into safe practice demands rigorous quality assurance and workflow optimisation. Institutions must establish clear adaptation criteria (action levels) and involve a dedicated multidisciplinary team to oversee the adaptive process. Comprehensive QA measures, including validation of deformable registrations, understanding the limitations in the application of AI-based algorithms, end-to-end testing of the adaptive workflow, and patient-specific verification of adapted plans (through secondary calculations or real-time dosimetry), are essential to ensure that adaptive interventions yield the intended benefit without compromising safety. In summary, adaptive radiotherapy is a powerful paradigm that, when supported by appropriate technology and QA processes, can enhance treatment efficacy and personalisation in radiation oncology, ultimately improving patient clinical outcomes.

Author contributions

T.P. – study concept, literature review, preparation of adaptive radiotherapy content for tomotherapy, supervision of the overall content, and manuscript writing; A.Z. – preparation and supervision of adaptive radiotherapy content for the Varian solution and manuscript writing; J.W. – preparation and supervision of adaptive radiotherapy content for MR-linac solutions and manuscript writing; M.D. – preparation and supervision of adaptive radiotherapy content for Elekta's EVO solution; A.S. – preparation and supervision of real-time tracking-based solutions and manuscript writing.

Competing interests

The authors declare no competing interests.

References

1. Hernandez V, *et al.* What is plan quality in radiotherapy? The importance of evaluating dose metrics, complexity, and robustness of treatment plans. Radiother Oncol. 2020;153:26-33. doi: 10.1016/j.radonc.2020.09.038
2. Jaffray D. Image-guided radiotherapy: from current concept to future perspectives. Nat Rev Clin Oncol. 2012;9:688-699. doi: 10.1038/nrclinonc.2012.194
3. McDonald BA, *et al.* Dose accumulation for MR-guided adaptive radiotherapy: From practical considerations to state-of-the-art clinical implementation. Front Oncol. 2023;12:1086258. doi: 10.3389/fonc.2022.1086258
4. Cheung J, *et al.* Dose Recalculation and the Dose-Guided Radiation Therapy (DGRT) Process Using Megavoltage Cone-Beam CT. Int J Radiat Oncol Biol Phys. 2009;74(2):583-592. doi: 10.1016/j.ijrobp.2008.12.034

5. Glide-Hurst CK, *et al.* Adaptive Radiation Therapy (ART) Strategies and Technical Considerations: A State of the ART Review From NRG Oncology. Int J Radiat Oncol Biol Phys. 2021;109(4):1054-1075. doi: 10.1016/j.ijrobp.2020.10.021
6. Aristophanous M, *et al.* Clinical Experience With an Offline Adaptive Radiation Therapy Head and Neck Program: Dosimetric Benefits and Opportunities for Patient Selection. Int J Radiat Oncol Biol Phys. 2024;119(5):1557-1568. doi: 10.1016/j.ijrobp.2024.02.016
7. Green OL, *et al*. Practical Clinical Workflows for Online and Offline Adaptive Radiation Therapy. Semin Radiat Oncol. 2019;29(3):219-227. doi: 10.1016/j.semradonc.2019.02.004
8. Lu L, *et al*. A Review of Online Adaptive Radiation Therapy. Appl Rad Oncol. 2024;5(1): (online ahead of print). doi: 10.37549/ARO-D-24-00037
9. Kisling K *et al*. Clinical commissioning of an adaptive radiotherapy platform: Results and recommendations. J Appl Clin Med Phys. 2022;23(12):e13801. doi: 10.1002/acm2.13801.
10. Hindmarsh J, *et al.* A dosimetric comparison of helical tomotherapy treatment delivery with real-time adaptation and no motion correction. Phys Imaging Radiat Oncol. 2025;34:100741. doi: 10.1016/j.phro.2025.100741
11. Czajkowski P, *et al*. Registration methods in radiotherapy. Rep Pract Oncol Radiother. 2019;24:28-34. doi: 10.1016/j.rpor.2018.09.004
12. Lavrova E, *et al.* Adaptive Radiation Therapy: A Review of CT-based Techniques. Radiol Imaging Cancer. 2023;5(4):e230011. doi: 10.1148/rycan.230011
13. Posiewnik M, *et al*. A review of cone-beam CT applications for adaptive radiotherapy of prostate cancer. Phys Med. 2019;59:13-21. doi: 10.1016/j.ejmp.2019.02.014
14. Ruchala K, *et al.* Megavoltage CT on a tomotherapy system. Phys Med Biol. 1999;44(10):2597-2621. doi: 10.1088/0031-9155/44/10/316
15. Tegtmeier RC, *et al.* Characterization of imaging performance of a novel helical kVCT for use in image-guided and adaptive radiotherapy. J Appl Clin Med Phys. 2022;23(6):e13648. doi: 10.1002/acm2.13648
16. Ng J, *et al.* MRI-LINAC: A transformative technology in radiation oncology. Front Oncol. 2023;13:1117874. doi: 10.3389/fonc.2023.1117874
17. Oderinde OM, *et al.* The technical design and concept of a PET/CT linac for biology-guided radiotherapy. Clin Transl Radiat Oncol. 2021;29:106-112. doi: 10.1016/j.ctro.2021.04.003
18. Onal C, *et al*. Dosimetric evaluation of ultra fractionated dose escalation with simultaneous integrated boost to intraprostatic lesion using 1.5-Tesla MR-Linac in localized prostate cancer. Rep Pract Oncol Radiother. 2024;29(1):10-20. doi: 10.5603/rpor.99358.
19. Ladbury C, *et al.* Biology-Guided Radiation Therapy: An Evolving Treatment Paradigm. Surg Oncol Clin N Am. 2023;32(3):553-568. doi: 10.1016/j.soc.2023.02.006
20. Datta A, *et al.* Delivering Functional Imaging on the MRI-Linac: Current Challenges and Potential Solutions. Clin Oncol. 2018; 30(11):702-710. doi: 10.1016/j.clon.2018.08.005
21. Wu C, *et al.* Real-time 4D MRI using MR signature matching (MRSIGMA) on a 1.5T MR-Linac system. Phys Med Biol. 2023;68(18): (epub ahead of print). doi: 10.1088/1361-6560/acf3cc
22. Chen GP, *et al.* Clinical Implementation and Initial Experience of Real-Time Motion Tracking With Jaws and Multileaf Collimator During Helical Tomotherapy Delivery. Pract Radiat Oncol. 2021;11(5):e486–e495. doi: 10.1016/j.prro.2021.01.010
23. Giacometti V, *et al*. An evaluation of techniques for dose calculation on cone-beam computed tomography. Br J Radiol. 2019; 92(1096):20180383. doi: 10.1259/bjr.20180383
24. Richter A, *et al.* Investigation of the usability of cone-beam CT data sets for dose calculation. Radiat Oncol. 2008;3:42. doi: 10.1186/1748-717X-3-42
25. Hu Y, *et al.* Synthetic CT generation based on CBCT using improved vision transformer CycleGAN. Sci Rep. 2024;14:11455. doi: 10.1038/s41598-024-61492-7
26. Hsu SH, *et al.* Synthetic CT generation for MRI-guided adaptive radiotherapy in prostate cancer. Front Oncol. 2022;12:969463. doi: 10.3389/fonc.2022.969463
27. Acquah IK, *et al*. A systematic review of deep learning techniques for generating synthetic CT images from MRI data. Pol J Med Phys Eng. 2025;31(1):20-38. doi: 10.2478/pjmpe-2025-0003
28. Simon A, *et al.* Roles of deformable image registration in adaptive RT: From contour propagation to dose monitoring. Proc IEEE Eng Med Biol Soc. 2015;2015:5215-5218. doi: 10.1109/EMBC.2015.7319567
29. Brock KK, *et al.* Use of image registration and fusion algorithms and techniques in radiotherapy: Report of the AAPM Radiation Therapy Committee Task Group No. 132. Med Phys. 2017;44(7):e43-e76. doi: 10.1002/mp.12256
30. Latifi K, *et al.* Practical quantification of image registration accuracy following the AAPM TG-132 report framework. J Appl Clin Med Phys. 2018; 19(4):125-133. doi: 10.1002/acm2.12348
31. Zhong H, *et al.* Deformable dose accumulation is required for adaptive radiotherapy practice. J Appl Clin Med Phys. 2024;25(8):e14457. doi: 10.1002/acm2.14457
32. Lim SY, *et al.* Dose accumulation of daily adaptive plans to decide optimal plan adaptation strategy for head-and-neck patients treated with MR-Linac. Med Dosim. 2022;47(1):103-109. doi: 10.1016/j.meddos.2021.08.005
33. Klein EE, *et al.* Task Group 142 report: quality assurance of medical accelerators. Med Phys. 2009 36(9):4197-4212. doi: 10.1118/1.3190392
34. de Pooter J, *et al*. Reference dosimetry in MRI-linacs: evaluation of available protocols and data to establish a Code of Practice. Phys Med Biol. 2021;66(5):05TR02. doi: 10.1088/1361-6560/ab9efe
35. Schreiner LJ. End-to-end QA in image-guided and adaptive radiation therapy. J Phys Conf Ser. 2019;1305:012062. doi: 10.1088/1742-6596/1305/1/012062
36. Nishioka S, *et al.* Identifying risk characteristics using failure mode and effect analysis for risk management in online MR-guided adaptive radiation therapy. Phys Imaging Radiat Oncol. 2022;23:1-7. doi: 10.1016/j.phro.2022.06.002
37. Wegener S, *et al.* Re-evaluation of the prospective risk analysis for AI-driven CBCT-based online adaptive radiotherapy after one year of clinical experience. Z Med Phys. 2024; 34(3):397-407. doi: 10.1016/j.zemedi.2024.05.001
38. Zhao X, *et al.* Do we need patient-specific QA for adaptively generated plans? Retrospective evaluation of delivered online adaptive treatment plans on Varian Ethos. J Appl Clin Med Phys. 2023;24(2):e13876. doi: 10.1002/acm2.13876
39. Olaciregui-Ruiz I, *et al.* Automatic dosimetric verification of online adapted plans on the Unity MR-Linac using 3D EPID dosimetry. Radiother Oncol. 2021;157:241-246. doi: 10.1016/j.radonc.2021.01.037
40. Tan X, *et al.* Fractional dose verification of intensity-modulated radiotherapy for cervical cancer based on exit fluences and log files. J Rad Res Appl Sci. 2023;16(1):100489. doi: 10.1016/j.jrras.2022.100489