

AI-Driven Quantitative Imaging in Radiotherapy: A New Era of Personalized Dosimetry

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Abstract: The evolution of artificial intelligence (AI) has had a significant impact on data acquisition, image reconstruction, and analysis across various fields, including radiotherapy. Concurrently, quantitative imaging has emerged as a formal discipline focused on extracting reliable physical measurements from medical images, thereby enabling a more objective assessment of disease extent. As a result, the synergistic integration of AI and quantitative imaging presents novel opportunities for personalized dosimetry in radiotherapy, potentially leading to improved patient outcomes.

Radiotherapy employs ionizing radiation to manage cancers and other benign conditions, with patient-specific dosimetry rules—emanating from clinical trials or consensus guidelines—deciding treatment strategies. Traditional dosimetry approaches, however, lack the capacity to accurately represent the nuanced variability inherent among individual patients. Consequently, AI-driven quantitative imaging offers the potential to quantify personalized signatures of radiation sensitivity and toxicity risk, paving the way for individualized treatment dose adjustments.

Drawing on extensive literature and future developments under consideration, this review elucidates the transformative influence of AI in

quantitative imaging and its relevance for personalized dosimetry. By facilitating more precise and tailored treatment plans, AI-driven radiographic quantification may enable significant advancements in radiotherapy by enhancing accuracy and reducing adverse side effects.

1. Introduction to AI in Radiotherapy

Radiotherapy significantly benefits from the thoughtful integration of innovative artificial intelligence (AI), advanced quantitative imaging, and personalized dosimetry. AI techniques, when applied to the realm of medical imaging, facilitate the automated detection of various anatomical and pathological objects, which consequently reduces the dependence on human operators while simultaneously increasing both speed and accuracy. Radiotherapy depends heavily on high-quality images for effective planning and precise treatment guidance; thus, quantitative imaging provides an essential and objective measure of important tissue properties that influence treatment decisions. When these cutting-edge methods are combined, they fundamentally enhance patient-level dosimetry, ultimately leading to more effective treatment plans that thoughtfully incorporate vital biological information, thereby reducing unwanted side effects. Furthermore, the concept of precision medicine involves customizing therapies based on measurable diagnostic indicators unique to each patient, and recent advancements in AI technology actively support and propel this personalized approach to care, making it ever more feasible and impactful for individual patient outcomes. [1] [2][3]

2. Fundamentals of Quantitative Imaging

Quantitative imaging extracts quantifiable features from medical images [4]. It includes tracer-kinetic features from dynamic contrast-enhanced MRI or dynamic-activity curves from dynamic PET for hypoxia, perfusion, and diffusivity. It has potential benefit for radiotherapy applications such as accurate target delineation, response monitoring and treatment stratification, and dose painting. Quantitative imaging is still mainly a research tool with limited clinical implementation, and considerable hurdles remain. Imaging characteristics differ across vendors and imaging protocols, while radiotherapy patient positioning is consistent between planning imaging and treatment delivery, highlighting the difference between diagnostic and radiotherapy imaging.

2.1. Definition and Importance

Quantitative imaging refers to the extraction and expression of inherent tissue properties as meaningful, measurable quantitative parameters from medical images. The QIB alliance defines quantitative imaging as the extraction of measurable features from medical images for the assessment of underlying pathophysiology, organ function, or evidence of disease [4]. Quantitative imaging plays an increasingly important role in future radiotherapy workflows, enabling accurate target delineation, response monitoring, treatment stratification, and dose painting. It is meant to be implemented safely and cost-effectively, with minimal impact on clinical workflow. Despite its potential benefits, quantitative imaging remains largely a research tool within radiotherapy. Significant barriers to clinical translation include technical challenges related to image consistency and reproducibility. Radiotherapy images obtained on different scanners and facilities, often using vendor-specific acquisition and reconstruction protocols, exhibit poor image standardization. Furthermore, images acquired with dedicated diagnostic protocols may not match the positioning or anatomical details required for radiotherapy treatment setup.

2.2. Technological Advances

In addition to the AI methodologies already presented, several data acquisition and image reconstruction techniques prove invaluable for enhancing the quantitative imaging datasets needed in radiation oncology. Strategies such as sparse-view CT—Acquisition of a reduced number of projections along multiple rotations to facilitate limited-angle reconstruction with additional axial rotations in a single breath-hold—enable low-dose quantitative imaging and high-frequency scanning; limited-angle CT—Retrieval of projections over a limited angular range—allows rapid response monitoring; and fast helical CT—Axial sampling acquired in a single breath-hold or during free breathing—supports motion-compensated reconstruction. These approaches adapt to clinical requirements, thereby extending daily patient monitoring capabilities with quantitative 3D imaging [5]. Together, these methodologies underpin a new paradigm in image-guided radiotherapy that enables the accurate delivery of nonuniform doses tailored to each individual's anatomy and physiology far beyond current capabilities [6].

3. Role of AI in Imaging

Quantitative imaging extracts quantifiable features from medical images to assess disease severity, evolution, or response to treatment [4]. By providing more detailed and reproducible information, it offers exciting opportunities for personalized radiotherapy (RT). Each QIB measures distinct physiologic, metabolic or functional information, yet all share the goal of relating image intensities to physical quantities — to produce image intensities that inform, rather than confound, clinical decisions. Enhancing the routine use of QIBs in RT would greatly advance personalized dosimetry, supporting the selection of appropriate treatments, lesion detection, and dose calculation methods. Yet, challenges remain to widespread acceptance of these techniques. Most are based on acquisition and reconstruction methods designed for diagnostic purposes, and RT imposes additional demands on patient positioning, image fidelity and quantification — all critical to accurate dose calculations and follow-up techniques. The quantitative imaging of individualized patient doses, therefore, calls for a new set of measurement techniques built around clinical problems rather than hardware solutions.

Machine learning (ML) builds on artificial-intelligence methods that automatically identify informative feature spaces from input data. It differs from classical algorithms ('programming') by enabling systems to improve over time through experience. ML techniques can capture complex relationships without explicit programming, learning from examples to make predictions or decisions [1]. Deep learning uses multiple processing layers to extract increasingly abstract representations, achieving remarkable accuracy in computer-vision applications by discovering intricate data structures. Both approaches constitute scientific advances that can systematically extract meaningful information, but they require sufficiently large quantities of reliable training examples. Quantitative imaging alone can provide a quantitative trigger for each acquisition, standardize reconstruction methods, and extract reliable measures for already acquired images. Only by linking the two can RT meet the urgent requirement for more robust techniques that accommodate various disease stages, patient morphologies, and acquisition protocols.

3.1. Machine Learning Algorithms

Artificial intelligence (AI) algorithms, within the subfield of quantitative imaging, have the potential to transform personalized radiotherapy dosimetry [7]. Machine-learning (ML) and deep-learning (DL) approaches have propelled quantitative imaging into a rich and rapidly evolving area of research. ML algorithms can discover hidden data relationships through unsupervised, supervised, or reinforcement learning and build predictive models [8]. DL, a specific computational model based on a multilayered artificial neural network architecture, has shown promising performances on heterogeneous and complex imaging data. The variety and dimensionality of such data constitute a challenge that can hardly be addressed by ML techniques such as state-space models or decision trees [9].

3.2. Deep Learning Techniques

Deep learning, a subset of machine learning, mimics the layered neuronal organization of the human brain and is the most popular contemporary AI approach to quantitative imaging. Presently, most applications employ deep neural networks, particularly convolutional neural networks (CNNs) [10]. CNNs were originally developed for image classification tasks and utilize a feature-extracting layer that searches for and displays features of the input using filters, similarly to how a biological neuron detects patterns through its dendrites [11]. CNNs have been used for image classification, segmentation, and registration, with 3-dimensional CNNs (3D-CNNs) emerging for volumetric and temporal analysis of medical images [12]. Models incorporating physics-informed networks are also gaining popularity, as they better preserve physical constraints during training. These systems typically include several interlinked neural networks trained simultaneously: one generates images, another estimates physical parameters, and a third converts output to the image domain for comparison with reference images. Such architectures can perform advanced functions such as image restoration, super-resolution, transformation, reconstruction, and radiation dosimetry. The quantity and quality of available data largely dictate the choice of computational architecture: small datasets often necessitate transfer learning, with models pretrained on large databases like ImageNet; deep models normally require 10,000–50,000 samples, whereas shallow models need 100–1,000 samples.

4. Personalized Dosimetry: An Overview

In radiotherapy, personalised dosimetry entails the optimisation and quantification of individual patient absorbed doses from radiopharmaceuticals to the tumour mass and healthy organs [11]. Historically, absorbed dose evaluations have relied on metrics that do not encapsulate the inherent heterogeneity of radioelement distribution within tumour and normal tissue [5].

The pioneering implementation of artificial intelligence (AI) in radiotherapy, dating from the 1990s, has evolved considerably, becoming integral to a broad spectrum of clinical applications. AI is now instrumental in enhancing nearly every phase of the radiotherapy workflow, from specimen preparation through treatment optimisation. The deployment of AI-driven quantitative imaging is poised to further personalise dosimetry from initial tumour localisation to delivery, facilitating the design of bespoke therapeutic plans that optimise tumour dose delivery while minimising exposure to healthy tissue. This technological trajectory is already demonstrating significant improvements in patient outcomes.

For the first time, AI offers the potential to generate a comprehensive quantitative map of all tissue properties as they vary with tumor uptake over time post-therapy. This advance enables personalised activity planning and refined dose delivery by providing essential dosimetry parameters directly extracted from patient images without recourse to theoretical assumptions.

4.1. Concept and Relevance

In the quest for personalized medicine, quantitative imaging is transforming radiotherapy dosimetry from a “one-size-fits-all” approach towards fully tailored therapy. Artificial intelligence (AI) integrates with individualized dosimetry through the provision of rapid imaging that captures the patient’s specific characteristics. Quantitative imaging encompasses methods that extract and measure tissue properties using signal or image content, often by converting images into digital data. Quantitative imaging now extends beyond parameter extraction into the realms of data acquisition and image reconstruction. Owing to the difficulties of modeling these steps or setting parameters for generic cases, AI emerges as a valuable tool.

AI has an active role in imaging, predominantly through machine-learning and deep-learning methodologies. Motivation for improved quantitative imaging derives from the limited value of images produced by radiation and nuclear-medicine detectors, which are currently used mainly for targeting and geometric guidance in radiotherapy. Emerging techniques from AI-driven quantitative imaging unlock new opportunities for high-value analysis, such as tumor detection,

staging, delineation, treatment response assessment, planning adaptation, and prediction of subsequent tendencies. [5] [1]

4.2. Challenges in Traditional Dosimetry

Film and thermoluminescence dosimetry are known to exhibit an intrinsic variability of about 5% [4]. Under such circumstances, the estimated incorporated activity at treatment planning is associated with large uncertainty, which eventually propagates to the prescribed tumor doses limiting the accuracy and precision of dose deposition predictions at treatment planning. Accurate and fast dose quantification techniques are then fundamental to assisting clinicians to devise better treatment strategies and optimal patient follow-up to interpret and assess treatment response or provide evidence for treatment change. Besides the clinical consequences, computational challenges are frequently encountered due to the sheer volume of data when quantitative imaging techniques are routinely employed [13]. Commercial software platforms in modern digital radiotherapy (RT) hardly provide sufficient temporal resolution and can be relatively time-consuming for the human operator even when semi-automated processing is implemented. Personalized molecular radiotherapy demands a complete dosimetry protocol involving a series of SPECT-CT scans for quantification of absorbed doses to tumours and normal organs [5]. Consequently, a scalable approach capable of bridging the gap between accuracy, precision, and speed is desirable. Quantitative imaging is a rapidly growing technique for measuring data units with physical significance in Radiotherapy.

5. Integration of AI and Quantitative Imaging

With the continuous development of artificial intelligence, the integration of artificial intelligence with quantitative imaging becomes the key technology to realize personalized dosimetry in radiotherapy [14]. The research of machine learning and deep learning techniques, especially convolutional neural networks, has led to a paradigm shift in artificial intelligence-driven bio-image analysis methods [5]. Quantitative imaging is used to extract numerous meaningful features. It is also used to enhance data acquisition and image reconstruction. Artificial intelligence improves data acquisition by enhancing signal-to-noise ratio and removing artefacts to optimize quantitative imaging [11]. It also helps to optimize imaging quality and reduce dose of imaging data acquisition. Artificial intelligence also benefits image reconstruction by producing new reconstruction algorithms to overcome limitations of traditional methods. In general, the integration of artificial intelligence and quantitative imaging makes it possible to extract imaging biomarker information more effectively.

5.1. Data Acquisition and Processing

Acquisition of accurate, high-quality quantitative imaging data remains crucial for personalized cancer dosimetry in ionizing radiation applications. Recently, AI-enhanced quantitative imaging data acquisition and processing methods have emerged, promising improvements in personalized treatment scenarios. A hybrid CT-linac regimen exhibits high clinical performance for non-urgent radiotherapy, while AI-assisted radiotherapy facilitates rapid delineation of normal tissue and organs at risk, automating the dose-mapping process [13] [15].

5.2. Image Reconstruction Techniques

Image reconstruction transforms raw imaging data into clinically interpretable images, with quality directly affecting downstream applications. AI methods, including deep learning, have been incorporated into quantitative imaging workflows to enhance reconstruction algorithms that model the imaging system. Such developments have improved image quality in tasks like breast tomosynthesis, electrical impedance tomography, and CT projection data. Deep learning-based reconstruction has also been employed in a radiotherapy environment, outperforming traditional filter back-projection algorithms [16].

6. Clinical Applications of AI-Driven Imaging

Artificial intelligence (AI) has offered promising individualized quantitative imaging and is redefining the qualitative evaluation of medical images [4]. Advances in computer vision imaging allow tumor detection, localization, characterization, and delineation for multiple cancer sites [11]. Applications of AI models include tumor shape analysis, treatment planning, organ segmentation, and image registration. AI-driven quantitative imaging significantly shapes personalized dosimetry and enhances patient treatment outcomes in cancer radiotherapy.

6.1. Tumor Detection and Characterization

The emergence of artificial intelligence (AI), including machine learning and deep learning, has created opportunities for adopting quantitative imaging methods that can transform the measurement of radiotherapy dose at both population and individual scales. These data-measured predictions can unveil minute details that traditional physics-modeled approaches overlook, enabling more accurate characterization of how sequencing and timing of radiation delivery in hypofractionated schedules alter dosimetry. Quantitative characterization of tumor delineation and motion through data-measured variation (based on AI approaches) therefore offers the prospect of realizing personalized dosimetry predictions.

Adequate staging and prognostication of any cancer dictate the effectiveness of therapeutic strategies for each patient. AI-driven quantitative imaging systems can incorporate tumor stage and prognostic information, alongside other relevant clinical data, into personalized strategies that assist clinicians during disease management [5]. Patients with a high visceral fat ratio, for example, demonstrate increased drug resistance and a poorer prognosis. Measurement of fat quantification from medical images, which is difficult to perform through manual inspections, can be expedited and made consistent using AI-based systems.

A number of commercial CT systems now include AI-driven semantic segmentation systems to assist clinicians. A variant of these approaches can be applied to radiotherapy; one recent study involving six deep-learning networks used techniques such as transfer learning, residual blocks, and reversibility to delineate the gross tumor volume (GTV) with an average single prediction error of 8.2%, compared to 13.2% reported for human delineations. Given that one of the major causes of inaccuracy and uncertainty in radiotherapy is delineation, these data- and knowledge-driven AI-based segmentation systems should lead to a reduction in safety margins and more targeted therapies centered on the promptly detected GTV [13].

6.2. Treatment Planning Optimization

The increasing complexity of intensity-modulated radiotherapy (IMRT) plans often necessitates significant user intervention during creation, leading to substantial average planning times. Efficient treatment planning optimization methods that reduce this user dependence thus become imperative [17]. Deep learning frameworks can estimate optimal radiation therapy dose distributions quickly and accurately from 3D patient anatomy, supporting the development of fully automated treatment planning systems that facilitate clinical integration [18]. Moreover, integrated systems capable of daily fast adaptive re-planning and gated/tracked radiotherapy enable smaller margins for uncertainty and tumour motion, diminishing dose to surrounding tissues and ultimately reducing treatment toxicity [5]. Auto-contouring systems embedded within planning platforms—based on image interrogation, statistical shape modelling, and atlas methods—further streamline the process by minimizing manual re-delineation. Machine-learning approaches assist automatic tissue detection and classification by learning image context and priors, while radiomics and radiogenomics extract quantitative information from medical images to enhance personalised radiotherapy.

7. Impact on Patient Outcomes

The integration of AI-driven quantitative imaging within the context of personalized

radiotherapy dosimetry is profoundly transforming treatment paradigms and positively influencing patient outcomes. Conventional dosimetry approaches are challenged by the significant variability inherent in individual patient anatomy and physiology [4]. AI-enhanced quantitative imaging captures personalized data relevant for individualized dose calculation; output metrics such as tumor volume, cell density, and tracer uptake now exhibit unprecedented precision. Clinicians benefit not only from subtle image details but also quantitatively measurable information not discernible by eye, enabling improved parameter estimation and model-of-choice selection. These objective, patient-specific insights engender more personalized and potentially efficacious radiotherapy plans.

7.1. Improved Accuracy and Precision

Radiotherapy is a mainstay of malignant tumor management and treatment worldwide, and radiation oncology is a field that in recent years has witnessed a rapid revolutionary momentum. This surge in progress, which derives mainly from advances at the forefront of the Artificial Intelligence (AI) stack, is challenging researchers to explore every possible corner in which to embed the relative algorithms. AI-driven quantitative imaging is established as a key enabling technology for personalized dosimetry in radiotherapy, holding the promising potential to transform current practices [8]. In the foreseeable future, it is expected that these technologies will transition from limited clinical settings into widespread global use. AI-driven quantitative imaging approaches hold promise for personalizing radiotherapy dosimetry, potentially improving patient outcomes and reducing side effects.

7.2. Reduction of Side Effects

Personalized radiotherapy dosimetry enables precise evaluation of dose distributions within a patient. Absorbed dose correlates closely with treatment response and risk of radiotherapy-induced toxicity. Artificial intelligence (AI)-driven quantitative imaging greatly facilitates the routine acquisition of high-quality quantitative images essential to personalized dosimetry, thereby reducing analysis uncertainties and minimizing side effects. Clinically, AI and associated technologies expedite routine tasks such as organ delineation and dose assessment. Seventy-five previously treated cases across head and neck, breast, and prostate cancers were analyzed based on auto-segmented organs-at-risk, with comparisons to patient treatment plans and expert-corrected contours. AI and AI-plus-correction methods generated comparable delineations, leading to significant dose-volume parameter changes in only 4% of cases. The application of AI resulted in a reduction of person-hours by 68% for breast, 51% for prostate, and 71% for head and neck malignancies [14]. The integrated system supports daily fast adaptive re-planning, which reduces margins for uncertainty and tumor motion, consequently decreasing the dose to normal tissues and lowering toxicity. Functional MRI acquired during treatment can guide adaptive focal boosting and enable personalized target dosing based on individual response, specifically targeting regions likely to respond poorly with additional radiation. Adaptive planning and AI facilitate real-time treatment modifications through image interpretation, segmentation, and plan optimization. Machine learning enhances image segmentation by automatically detecting and classifying tissues, assisting in re-delineation and plan creation. Radiomics techniques extract quantitative information about tumor physiology from medical imaging, offering valuable data for personalized radiotherapy planning. Pattern recognition tools are employed to analyze this high-dimensional data, enabling the identification of meaningful clinical correlations [5].

8. Ethical Considerations in AI Applications

A comprehensive grasp of ethical standards guiding AI use in healthcare remains essential. Matters of patient data confidentiality, information ownership, and adherence to foundational principles consistently emerge as concerns. Considerations around AI reliability, latent ethical conflicts, bias, legal responsibility, and inequity require ongoing vigilance. Embedding ethical perspectives within AI development—supported by structured frameworks—supports

responsible deployment. Input from practising radiographers offers valuable insight into potential repercussions of adopting AI [19]. Bias and fairness constitute intertwined challenges; practitioners underscore the necessity of addressing partiality, as algorithmic judgements can reinforce health disparities [20]. Perceived fairness influences public trust and acceptance, highlighting the importance of monitoring equitable treatment.

8.1. Data Privacy and Security

Artificial intelligence (AI) is profoundly transforming radiotherapy, and high-quality data remain its lifeblood. Health data are particularly sensitive because they concern individuals, so their use in AI development raises specific ethical considerations, including privacy, dignity, and safety, which also apply to health data used in AI training. Breaches of health data pose risks to the privacy and safety of individuals and institutions and can, through data misappropriation, lead to discrimination and victimization. To ensure that health data are used responsibly, organizations and countries have enacted various regulations such as the European Union's General Data Protection Regulation (GDPR). Violations of data protection laws can result in the deletion of datasets regardless of their quality or commercial value, and the individuals affected are entitled to compensation for both material and moral harm.

The ethical design of an AI model requires strict adherence to these rules throughout the product lifecycle, extending to data collection, model construction, training, and usage. Malicious or careless data leakage can harm patients and erode their trust in the model and its providers. Conversely, employing reliable and accurate AI systems for data handling can generate high-value data, thereby benefiting patients, boosting research, and ultimately improving treatment outcomes. In radiotherapy, patient privacy—which often serves as an argument for withholding data sharing—remains the top priority, regardless of whether data are shared nationally or internationally.

8.2. Bias and Fairness in AI Models

Radiotherapy is a long-established therapeutic technique that employs ionizing radiation to treat tumors. Personalization of dose delivery ensures optimal outcomes and reduced burden to healthy tissue. Quantitative imaging is a technique generating images with voxel values representing quantitative physical, chemical, or biological features. It can be utilized for *in vivo* assessment of tissue injury and for the prediction of radioresponse prior to the delivery of any radiation dose. Personalized dosimetry for radiotherapy can thus, be based on quantitative imaging and coupled with artificial intelligence (AI).

9. Future Directions in AI and Radiotherapy

Cutting-edge technology is poised to extend dosimetry into new unanswered and unimagined realms. Real-time AI-driven imaging can be combined with tumor tracking to create a new level of treatment personalization. Functional and molecular imaging can provide unattainable knowledge on tumor biology and normal tissue responses for safe and effective bio-adaptive protocols. Although ethical considerations remain at the forefront of AI-driven medical devices, AI technology also creates opportunities for new investigative and monitoring instruments for automation and quality assurance. On a regulatory front, AI software solutions are expected to conform to FDA regulations, international standards, and ongoing guidance documents. In the next frontier for AI applications in radiation oncology, the field will see new research themes emerge around multidisciplinary collaboration involving medical experts, imaging specialists, physicists, and engineers. Insights from industries such as aerospace, automotive, and software are also expected to fuel creative innovations in medical image analysis. A consequent need arises for integrated scientific workshops and university programs that educate would-be practitioners about the theory and practice of AI-enabled dose calculation. Finally, strategies must be developed to enhance patient engagement with AI solutions through educational materials, informed consent processes, and continued dialogue that employs clear, accessible

language. The potential of AI-driven quantitative imaging to enable personalized dosimetry is becoming widely accepted and is poised to bring a new paradigm to radiotherapy. [1]

9.1. Emerging Technologies

AI applications became an integral part of radiotherapy years ago; yet, advances in artificial intelligence (AI) promise to transform the field. Quantitative imaging extracts and calibrates information from medical images, yielding physiologically relevant parameters. Recent generations of imaging instruments, as well as innovative data acquisition and image reconstruction technologies, provided the foundation for widespread adoption of quantitative acquisition. AI accelerates quantitative data acquisition, supports dedicated reconstruction techniques for quantitative information, and enables efficient image-analysis pipelines for extraction of physiologically relevant biological readouts. Large availability of AI-driven infrastructure will set the stage for high-throughput clinical implementation of quantitative-imaging components in personalized radiotherapy-dosimetry protocols.

Emerging technologies provide numerous opportunities for novel radiotherapy applications. Development of an image-integrated linear accelerator motivated clinical investigation of biological adaptive radiotherapy from the perspective of x-ray acquisition and quantitative image reconstruction. Preliminary investigations of tumor microenvironment follow-up quantified the potential roles of AI-driven quantitative imaging in personalized dosimetry for the treatment of lung-cancer patient cohorts [1].

9.2. Long-Term Research Goals

Artificial intelligence-driven quantitative imaging has the potential to transform the practice of personalized dosimetry. Current developments in the domains of diagnostic and molecular imaging are enabling the creation of tailored dosimetry models optimized for individual tumors and organs. The resulting enhancements in radiotherapy planning promise to reduce side effects, improve accuracy, and deliver superior clinical outcomes. Nonetheless, the addition of advanced technologies to the clinical workflow simultaneously raises important ethical concerns related to data privacy and security. Moreover, as artificial intelligence is applied to patient care, clinicians must carefully evaluate potential biases to ensure that the approaches in deployment are both equitable and fair.

Emerging paradigms in data acquisition suggest that the conventional patient-patient, patient-clinician, and clinician-machine data acquisition models of today will yield to models in which the control of modalities is delegated to the artificial intelligence system itself. This “self-driving” concept has the potential to revolutionize the field by generating tailored acquisition protocols specifically optimized for the individual patient undergoing a scan, thus moving toward a genuine personalized medicine approach. In this context, the development of innovative systems will inevitably be influenced by the need to balance the objectives of personalization and customization with more general considerations of safety and trust. [21][22][23]

10. Case Studies

Real-world case studies provide crucial insight into AI-driven quantitative imaging for personalized radiotherapy dosimetry. The potential to deliver an accurate and efficient workflow has been realized in a hybrid computed-tomography linear-accelerator system [15]. Full automation from image acquisition to treatment planning enabled straightforward rectal-cancer proton therapy and demonstrated the approach for institutions initiating AI application. Week-long treatments in complex head and neck cancer and multiregion breast-cancer care also showed promise when combined with human review, illustrating the balance of speed and accuracy.

During initial treatment, fully automated tools may compete with resource-intensive, manual contour correction—highly personalized methods may be faster than tiers of iterative

computational design. Because the All-in-One solution relies on the original data, however, repeated adaptive sessions remain effective for propagation of contours and dose objectives. Integrated, data-driven models enable rapid delineation of the tumour and critical structures, with sound prediction of necessary radiation exposure; the organization and application of this information in treatment plans reduces toxicity and accommodates rapidly changing clinical needs [5]. Segmentation accuracy is sufficient for clinically acceptable dose–volume histograms and absorbed doses in a range of cancer types with significant time savings compared with fully manual delineations [14]. Improvements to initial imaging and adaptive workflows will be critical to clinical deployment.

Failures, often reflecting organizational challenges rather than technical deficiencies, reinforce lessons for future implementation. Early adoption followed a business-case rounding strategy rather than a patient-centred evaluation. Additional executive priorities impeded adoption in some contexts for up to two years. Even successful application in data-driven ground-truth generation cannot replace hands-on involvement for understanding the artefacts, uncertainties, and later model improvement. Careful consideration of historic practice, cultural change, and patient needs are necessary to ensure dependable performance at scale.

10.1. Successful Implementations

The All-in-One solution introduces a hybrid CT-linac framework that enables full-process automation of online adaptive radiotherapy for rectal cancer. Clinical outcomes corroborate the delivery of accurate and efficient treatment within a one-stop workflow. This approach refines workflow effectiveness and holds promise for advancing the clinical adoption of online adaptive radiotherapy [15].

10.2. Lessons Learned from Failures

Recent advances demonstrate that the successful development of a reliable AI-driven approach for personalized radiotherapy dosimetry mandates a nuanced understanding of the requirements and limitations of the adopted AI techniques. Deep learning models, exemplified by multilayer convolutional neural networks, are extensively utilized in this context, enabling image-quality enhancement, registration, and segmentation. Moreover, the integration of generative and self-supervised learning paradigms holds promise for further elevating analysis performance. Machine-learning-driven quantitative imaging, therefore, constitutes a robust methodology for improving personalized dosimetry. Concurrently, tested implementations allow the identification of the fundamental prerequisites and potential applications associated with these AI-driven techniques. Basic functionalities, such as median value filtering and forward peak detection, extend accessibility beyond highly experienced users. Sharing data between manufacturers and clinicians emerges as a key strategy for optimizing predictive potential. The evaluation of established simulation tools becomes indispensable in this framework, with aspects such as algorithms, accuracy, and measurement time taking precedence over imposed limitations [9] [8].

11. Regulatory and Compliance Issues

AI-driven personalized dosimetry must comply with existing FDA regulations to ensure patient safety and treatment efficacy. The FDA considers machine-learning programs initially as medical devices under the 21st Century Cures Act, necessitating premarket clearance through either the de novo pathway or the 510(k) procedure [1]. Specific AI algorithms for oncological medical imaging have been approved under regulations stipulating that AI technologies must provide information that aids rather than replaces the physician's decision-making [24]. Product labelling should explicitly state the intended use and the nature of the algorithm, whether diagnostic or prognostic.

Lack of model interpretability challenges validation, and no standard exists for demonstrating substantial equivalence for AI-driven quantitative imaging integrated with modern external beam radiotherapy treatment planning. Beyond FDA regulations, recommendations by global medical-

physics organizations guide the safe clinical deployment of AI-based medical technologies.

11.1. FDA Guidelines for AI in Healthcare

This section outlines the US Food and Drug Administration (FDA) regulatory framework for artificial intelligence (AI) software in healthcare. It notes that the FDA regulates the sale and distribution of medical devices to ensure their safety and effectiveness. Software, including software containing AI, meets the statutory definition of a device when it is intended for medical purposes.

Section 11.1.FDA guidelines for AI in healthcare

FDA's regulatory framework for AI software in healthcare is consistent with the agency's overall approach to regulating software as a medical device. FDA regulates the sale and distribution of medical devices to ensure their safety and effectiveness. Software (including software containing AI) meets the statutory definition of a device when it is intended for a medical purpose (e.g., diagnosing disease or other conditions, or curing, mitigating, treating or preventing disease) [14].

11.2. International Standards and Protocols

Standards and protocols form the foundation for enhanced reproducibility in healthcare and, consequently, play a vital role in the safe implementation of AI tools. The FDA articulated this aspect as early as 2019 when addressing Digital Health policies. Ensuring consistent image realism, the Qualitative Assessment of Synthetic Images (QUASIMODO) protocol offers a structured approach to assess fidelity. Internationally, the International Electrotechnical Commission (IEC) has issued Radiotherapy Quality Assurance (QA) standards for equipment and software under IEC 62083 and IEC 61217, addressing some requirements for AI tools. Physicists have developed specialized QA procedures supporting model integrity and traceability, such as those available in QA Network, while several studies propose methods to guarantee safety and transparency in AI developments. Recent efforts by the European Commission aim to establish new guidelines for AI in medical devices, anticipating stronger international regulatory harmonization in the future [4].

12. Collaboration Between Disciplines

Interdisciplinary research activities between the medical domain and computer science are vital for the advancement and dissemination of AI developments in radiotherapy. Such cross-sector collaborative efforts allow the rapid translation of emerging AI capabilities into clinical practice via a coordinated framework that includes preclinical development, clinical trials, and real-world implementation. Partnerships between academia and industry establish complementary teams that facilitate the evaluation of open problems and the creation of proof-of-concept solutions. Medical institutions and practitioners provide clinically relevant data sets and define appropriate questions based on investigation findings. Academic AI specialists offer advanced techniques and wide-ranging exploration of existing algorithms. Commercial companies contribute know-how and technologies related to regulated development, assistance with clinical trials, and integration into everyday clinical workflows [5].

12.1. Interdisciplinary Research Teams

The rise of machine learning has accelerated interdisciplinary research in the AI-healthcare domain. Collaborative effort by academic and industrial partners facilitates the development of innovative AI approaches to transform the state of the art and improve clinical care.

The integrated system allows for daily adaptive re-planning in radiotherapy, thereby reducing margins for uncertainty and tumor motion and, consequently, damage to surrounding tissue and toxicity. Functional MRI during treatment makes it possible to deliver an adaptive focal boost based on response: an extra dose is delivered to parts of the tumor that are responding poorly.

12.2. Industry and Academia Partnerships

Industry–academia partnerships play a vital role in the development and deployment of artificial intelligence (AI) technologies, facilitating the transition of oscillator-generation and data-driven models from research to clinical practice in personalized radiotherapy dosimetry [11].

Government funding and access to preclinical data initiate the cycle of validating AI models as valuable clinical tools. Collaborative agreements specify the scope of rights and usage, enabling researchers to design standardized, streamlined platforms for multi-scale data integration. Commercial partnerships help to secure intellectual property, with shared revenue streams providing late-stage funding.

Expertise combined with large-scale data processing and powerful computational resources accelerates model development and deployment before potential outlet by other groups or products. Coordination of proprietary patient data and models enables negative data bias and evaluation of AI-powered solutions in perspective, maintenance, and guidance.

13. Training and Education for Practitioners

The incorporation of AI-driven quantitative imaging into radiotherapy necessitates a comprehensive restructuring of professional education and ongoing training frameworks. To maintain high standards and fully exploit technological advancements, curricula must integrate foundational courses in AI frameworks alongside image analysis, radiotherapy planning, and multi-modal fusion techniques. Supplementary workshops facilitate the acquisition of practical skills and transition from theory to clinical practice. Empirical evidence underscores an acute shortage of both formal guidelines and educational resources to support the widespread clinical application of machine learning and AI in the field. Esteemed organizations such as ESTRO, AAPM, and EFOMP are actively addressing these gaps by enhancing educational programs for medical physicists. The urgent need for detailed commissioning and implementation protocols — refined to meet the unique challenges associated with AI-based radiotherapy products — is paramount. Comprehensive recommendations are essential to guide clinical teams through the integration of machine learning models tailored for contouring, planning, and synthetic CT generation. Furthermore, clinician education emerges as a critical requirement, with a considerable majority endorsing the establishment of multidisciplinary courses that encapsulate the breadth of AI algorithms, dataset characteristics, and operational limitations necessary to optimize collaborative human–machine interactions. With AI integration currently operative in approximately 37 % of radiotherapy clinics and widespread expansion anticipated, the reinforcement of structured guidance on commissioning and rigorous quality assurance procedures constitutes a core priority for ensuring safe and effective implementation [24] [25].

13.1. Curriculum Development

Education has always been a cornerstone of the radiotherapy profession, particularly in the domain of quantitative imaging, where the critical need for novel AI-driven methodologies persists [17]. Quantitative imaging can be simply defined as the extraction of data from medical images with the objective to enhance diagnosis, personalize the treatment pathways, and consequently improve the clinical outcome.

From an educational perspective, quantitative imaging can serve as a fertile learning experience for students and newcomers. It offers an ideal background to re-explore fundamental concepts of existing medical imaging modalities, which acquire renewed significance when considered through a quantitative lens. Additionally, it encourages students to innovate in imaging systems and reconstruction methods, with the aim of optimizing the extraction of quantitative information or reducing the uncertainties linked to estimation. Beyond the purely scientific and technical realm, this field also opens avenues for critical examination of potential adverse effects stemming from widespread implementation. These effects might particularly impact patients and providers, emphasizing the need for ongoing discussions on equitable access and the

establishment of social control mechanisms to prevent misuse or teratogenic interference in medical decisions.

13.2. Workshops and Continuing Education

Workshops and continuing education play vital roles in promoting the translation of cutting-edge research into clinical practice, helping to train the next generation of practitioners, and supporting colleagues already working in a particular domain. Examples illustrating the implementation and impact of professional development initiatives in quantitative imaging and AI applications are presented.

With a growing number of imaging options available during radiotherapy, ongoing training linking appropriate imaging selection to disease setting is important for ensuring that the full capabilities of available hardware are exploited and the choice of imaging technique is fully informed by considerations of cost, accuracy, invasiveness, and unintended side effects. Nuclear medicine-dosed PET/CT scanning, for example, can deliver 30 mSv or more of effective dose, whereas a simple X-ray planar imaging procedure may deliver only a few μSv [26]. Workshops, therefore, focused on the strengths and weaknesses of different image modalities, imaging safety, clinical artifact recognition, clinical contouring variation, and the impact of imaging on treatment outcome will be increasingly important. Sharing best practice between teams and between academic research centres and commercial organisations, and leveraging advances in technology to develop novel, efficient, and more detailed qualitative and quantitative analysis tools can help accelerate progress in the domain and maximize the benefit available to patients.

14. Patient Engagement and Communication

Thorough patient communication is paramount for informed consent and acceptance of artificial intelligence (AI) technologies. In support of the clinical intent, genuinely informative patient materials must address more than procedural objectives and safety to cultivate trust, fulfill governance requirements, and avoid the rejection of AI systems. Effective communication strategies are thus essential for establishing patient trust and facilitating informed decision making [27].

14.1. Informed Consent Processes

Informed consent processes enable individuals to make voluntary and educated decisions about medical interventions. Standardized informed consent forms are utilized to capture demographic details and document patient approval, thereby facilitating transparent and ethical communication. Properly addressing informed consent is crucial for ensuring patient understanding, maintaining trust in healthcare, and complying with legal and ethical standards.

14.2. Patient Education Materials

The complexity of radiation therapy treatments necessitates effective patient-clinician communication regarding procedures, benefits, risks, and safety precautions to foster informed decision-making and adherence to care plans. Patient education materials serve as valuable supplements to verbal explanations, as time constraints often limit thorough patient understanding during consultations. Advanced personalized dosimetry techniques such as artificial intelligence (AI)-supported adaptive radiotherapy require explanation through comprehensive, easily accessible educational materials tailored to diverse literacy levels [28]. Multimedia formats, including video content, and considerations of psychological factors like anxiety and uncertainty, as well as local cultural influences, should inform the development of these materials to optimize comprehension and trust [29]. Distribution should be broad and address topics such as available treatment options, diagnostic procedures, processes for participating in clinical trials, access to travel and accommodation support, potential long-term and delayed treatment effects, and survivorship support beyond hospital settings [30].

15. Conclusion

The integration of artificial intelligence (AI) in radiotherapy has catalyzed a transition from qualitative to quantitative image processing, fostering new levels of personalization in dosimetry. Quantitative imaging extracts and analyzes measurable physical features from images; when AI-driven, the emerging discipline is termed AI-driven quantitative imaging. Through enhanced acquisition and reconstruction, AI-powered techniques afford imaging of higher quality, faster speed, greater reproducibility, and increased diagnostic accuracy for individual patients. The acceptance of AI-based quantitative imaging across radiology, nuclear medicine, and radiotherapy underpins new paradigms of data-driven personalized treatment and dosimetry. Such advances help patients by improving dose accuracy, minimizing treatment side effects, and facilitating compliance with prescribed therapy schedules.

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