Role of AI in the Clinical Practice of Radiation Oncology: What Does the Future Hold?

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Abstract: ***Artificial intelligence (AI) is rapidly transforming healthcare and is increasingly entering routine radiation oncology practice. Current applications include image registration, automated segmentation, treatment planning, plan evaluation, image-guided and adaptive radiotherapy, quality assurance, radiomics and prediction of treatment response and toxicity. Among these, deep-learning-based auto-contouring and knowledge-based treatment planning are among the most mature applications. AI is also beginning to bridge radiation oncology with radiology, nuclear medicine, digital pathology, chemotherapy and immunotherapy by integrating multimodal clinical and biological information. However, technical performance does not necessarily translate into clinical benefit. Dataset bias, limited external validation, domain shift, automation bias, lack of explainability, cybersecurity, privacy, regulatory uncertainty and accountability remain important challenges. The future of radiation oncology is therefore unlikely to be one of replacement of clinicians by machines. Rather, AI is likely to become a clinical co-pilot that performs computationally intensive and repetitive tasks while radiation oncologists retain responsibility for interpretation, contextual judgement, communication and ethical decision-making. The challenge for the next generation of radiation oncologists is not to compete with AI but to learn how to work safely and intelligently with it. Ultimately, AI can enhance precision and efficiency, but it cannot replace the human connection at the heart of cancer care.***

Keywords: Artificial intelligence; radiation oncology; machine learning; auto-contouring; adaptive radiotherapy

1. Introduction

Radiation oncology has evolved through successive technological revolutions- from two-dimensional planning to three-dimensional conformal radiotherapy, IMRT, VMAT, stereotactic techniques and image-guided and adaptive radiotherapy. Each advance has increased precision, but also increased workflow complexity.

Artificial intelligence (AI) represents the next major transition. AI refers broadly to computational systems capable of performing tasks that require aspects of human intelligence, such as pattern recognition, classification, prediction and optimisation. Machine learning (ML) enables algorithms to learn relationships from data, while deep learning (DL), using multilayer neural networks, can extract increasingly complex patterns from large datasets.[1–3]

Radiation oncology is particularly attractive for AI because virtually every stage of care generates digital data—CT, MRI and PET images, contours, dose distributions, treatment parameters, laboratory values, pathology, toxicity and outcomes. AI can therefore potentially influence the entire pathway, from diagnosis and target delineation to treatment delivery and outcome prediction.[4,5]

The question is no longer whether AI will enter radiation oncology. It already has. The important question is how clinicians can use it safely without losing the human judgement that defines cancer care.

How Does AI Work in Radiation Oncology?

At its simplest, an AI system learns a relationship between an input and a desired output. The crucial distinction is that **AI output is not equivalent to a clinical decision**. The output must be interpreted in the context of tumour biology, anatomy, treatment intent, comorbidities, patient preferences and uncertainty. These aspects are highlighted in figures 1 and 2.

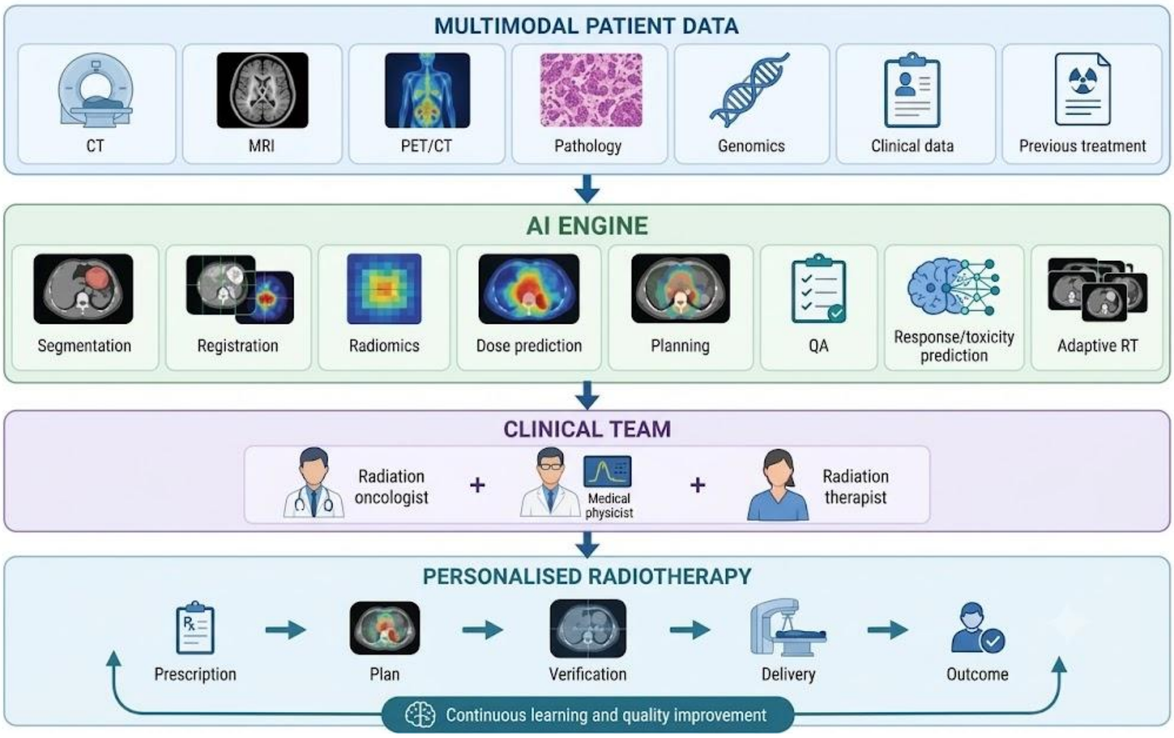

Figure 1: Conceptual representation of AI as an integrating layer across the radiation oncology workflow. AI assists rather than replaces clinical decision-making

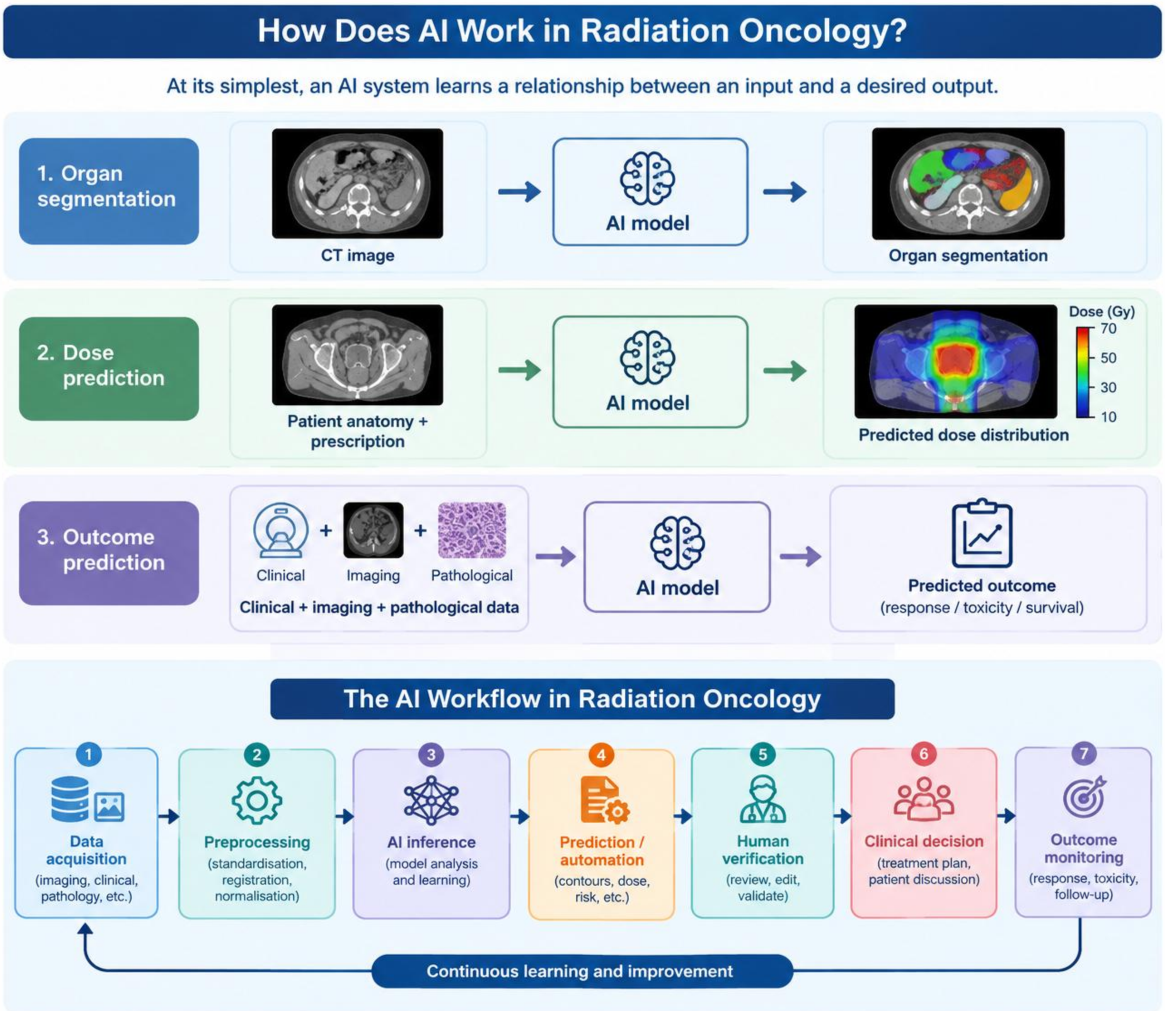

Figure 2: AI-enabled radiation oncology workflow

AI in Radiotherapy Planning: From Contouring to Adaptive Treatment

Auto-contouring: the gateway application

Manual delineation of target volumes and organs at risk (OARs) is time-consuming and subject to interobserver variability. Deep-learning auto-segmentation has therefore become one of the most clinically mature applications of AI in radiation oncology.[6-9] OARs such as the spinal cord, brainstem, parotids, lungs, heart, kidneys, bladder and rectum can often be segmented rapidly and consistently. Target delineation remains more challenging because it requires interpretation of tumour biology, microscopic spread, postoperative changes and multimodality imaging. Recent literature highlights both the efficiency gains and the risks of target-volume auto-segmentation.[7,9]

The value of auto-contouring extends beyond saving time. It can reduce variability, standardise nomenclature, facilitate multicentre trials and make rapid adaptive radiotherapy more feasible.

However, an AI contour should be regarded as a clinician's first draft- not the final contour. A small geometric error near the optic chiasm, spinal cord, cochlea, bowel or tumour interface may have major clinical implications. NRG Oncology has emphasised the need for clinical validation and structured quality assurance before widespread adoption.[6]

AI-driven treatment planning

The next step is automated planning. Knowledge-based planning and deep-learning models can predict dose distributions from anatomy and previous high-quality plans and use these predictions to guide optimisation.[10,11]

The potential benefits include:

- Reduced planning time;
- Greater consistency between planners;
- Rapid generation of alternative plans;
- Objective identification of suboptimal plans; and
- Greater feasibility of adaptive radiotherapy.

AI therefore changes the role of the planner from repeated optimisation towards **supervision, interrogation and exception handling**.

Adaptive radiotherapy

Adaptive radiotherapy requires repeated assessment of anatomy and, when necessary, modification of the treatment plan. Its clinical implementation is often limited by the time required for contouring, plan generation and verification.

AI can accelerate image registration, contour propagation, dose prediction and replanning, potentially enabling more practical online adaptation.[4,5]

Table 1: Applications of AI across the radiotherapy pathway

RT stage	Potential AI application	Current position
Imaging	Reconstruction, denoising, registration, synthetic CT	Emerging
Contouring	OAR and selected target segmentation	**Clinically mature**
Planning	Dose prediction, knowledge-based planning	**Increasing clinical use**
Plan evaluation	Automated DVH and constraint assessment	Emerging
IGRT	Image matching, motion detection	Emerging
Adaptive RT	Rapid contouring and replanning	Emerging
QA	Automated plan and machine-error detection	Emerging
Radiomics	Imaging biomarkers	Mainly investigational
Outcome prediction	Tumour control and toxicity prediction	Investigational
Decision support	Multimodal treatment recommendations	Early stage

AI Beyond the Radiation Oncology Department

Radiotherapy is increasingly integrated with other oncology disciplines. AI may eventually provide a common platform connecting these data streams.

Radiology

AI-assisted radiology can support lesion detection, segmentation, quantitative imaging and response assessment. Radiomics converts medical images into quantitative features that may provide information beyond conventional visual interpretation.[12–14] Such information could influence target delineation, response assessment and treatment adaptation.

Oncopathology

Digital pathology enables AI-based tumour detection, grading and quantitative assessment of histological and molecular features.[15] Integration of pathology with imaging and treatment data could potentially generate **radiogenomic and pathomic signatures** associated with treatment response.

Nuclear medicine

AI is increasingly being explored for PET image reconstruction, segmentation, quantitative analysis and radiomics.[16] This may improve biological target identification and response assessment and could have future implications for theranostic approaches.

Chemotherapy and immunotherapy

AI is also being investigated for prediction of chemotherapy response, drug sensitivity and treatment toxicity.[17,18] In immuno-oncology, AI may integrate imaging, pathological, molecular and clinical features to identify patients more likely to respond to immune checkpoint inhibition.

This becomes particularly relevant to **radioimmunotherapy and chemoimmunotherapy**, where treatment response depends on complex interactions between tumour biology, immune status, systemic therapy and radiation dose. At present, these applications remain largely investigational, but they illustrate the potential for AI to move oncology from single-modality decision-making towards integrated precision treatment.

Ethical Concerns and Clinical Pitfalls

The greatest challenge may not be whether an AI model works in a research environment, but whether it remains reliable when deployed in a different hospital, scanner, population or workflow.

Important concerns include:

- **Bias and generalisability:** Models trained predominantly on one population may perform differently elsewhere.
- **Automation bias:** Clinicians may accept an AI output simply because it appears objective or computationally sophisticated.
- **Explainability:** Many deep-learning systems provide an answer without adequately explaining why.
- **Data privacy:** Imaging, clinical and genomic datasets contain highly sensitive patient information.
- **Accountability:** Responsibility must remain clearly defined when AI contributes to a clinical decision.
- **Algorithm drift:** Performance may deteriorate as scanners, imaging protocols, patient populations and clinical practice change.
- **Cybersecurity:** AI systems integrated with hospital networks introduce additional security vulnerabilities.
- **Deskilling:** Excessive reliance on automation could gradually erode clinicians' independent skills.

The WHO emphasises autonomy, safety, transparency, accountability, equity and appropriate governance in healthcare AI.[19]

Table 2: Major pitfalls of AI in radiation oncology

Problem	Potential consequence	Safeguard
Dataset bias	Unequal performance	Diverse multicentre datasets
Domain shift	Reduced accuracy after deployment	Local validation
Auto-contour error	Geographic miss/OAR overdose	Mandatory clinician review
Automation bias	Uncritical acceptance	Human-in-the-loop workflow
Black-box prediction	Poor interpretability	Explainability/ uncertainty estimates
Algorithm drift	Declining performance	Continuous monitoring
Poor interoperability	Workflow disruption	Standardised data architecture
Data breach	Loss of patient privacy	Robust cybersecurity
Skill erosion	Loss of clinical expertise	AI-aware training

Technical accuracy alone is insufficient. AI systems require **external validation, prospective evaluation, clinical commissioning and continuous post-deployment monitoring.**[6,9,20]

Can AI Replace the Radiation Oncologist?

AI can potentially contour faster, process more data, identify patterns and optimise treatment plans more rapidly than a human. But the radiation oncologist does more than calculate a plan. The clinician decides **whether** treatment should be given, **why** it should be given, **how** it fits within the patient's overall cancer journey and **what matters most to the patient**. A machine can identify a contour; it cannot fully understand its clinical meaning. A machine can estimate toxicity; it cannot explain that risk to a frightened patient. A machine can generate a treatment plan; it cannot take moral and professional responsibility for the decision to treat. Thus, the likely future is not replacement but **role transformation**.

Figure 3: From automation to augmentation

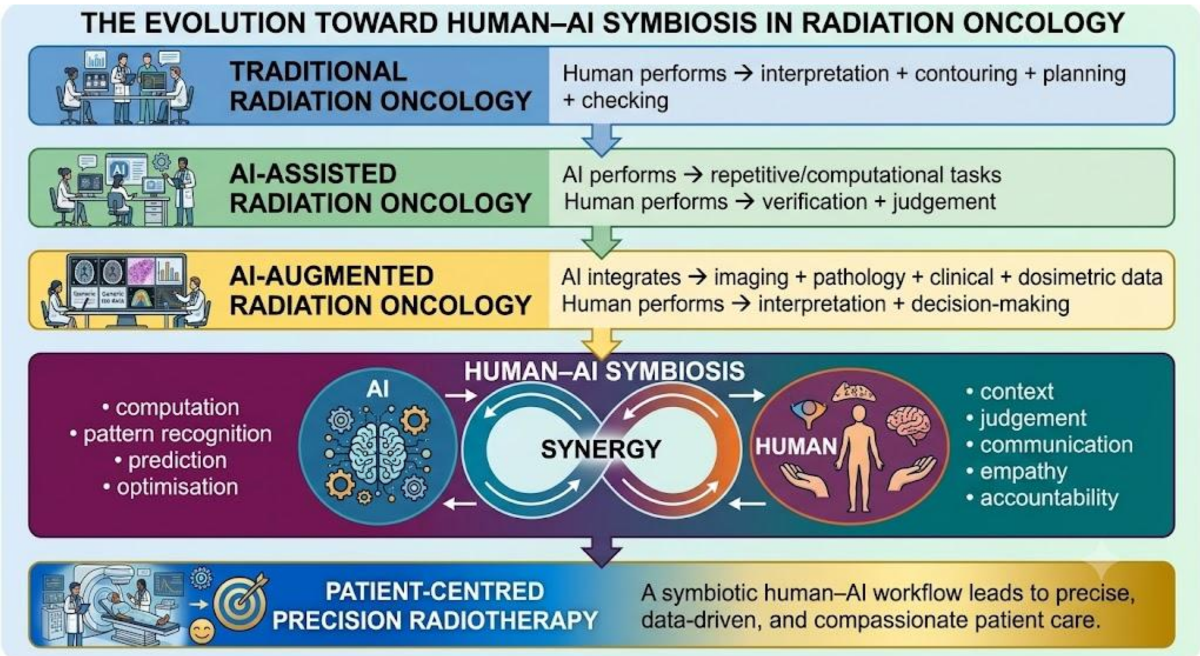

Figure 3: The anticipated evolution of AI in radiation oncology is from task automation towards human-AI augmentation, rather than autonomous replacement of clinicians

How Do We Learn to Live With AI?
Radiation oncologists should not attempt to compete with machines at tasks for which machines are inherently better. Instead, clinicians need **AI literacy**. The radiation oncologist of the future should understand:
- What data trained the model;
- Where the model has been validated;
- When it may fail;
- How uncertainty is expressed;
- How to recognise an implausible output;
- How to audit performance; and
- When to override the algorithm.

AI education should therefore become part of radiation oncology training. This does not mean that every radiation oncologist must become a data scientist. Rather, clinicians need sufficient understanding to **question AI intelligently rather than accept it blindly**.[21]

Table 3: Human–AI symbiosis in radiation oncology

AI can increasingly provide	Human clinician must retain
Rapid segmentation	Final contour approval
Dose prediction	Prescription and treatment intent
Plan optimisation	Clinical plan selection
Large-scale data analysis	Contextual interpretation
Risk prediction	Shared decision-making
Automated QA alerts	Safety accountability
Literature/data synthesis	Clinical judgement
Workflow automation	Communication and empathy

What Does the Future Hold?
The next generation of AI in radiation oncology is likely to move from isolated applications towards **multimodal clinical intelligence**.

Potential developments include:
1) **Multimodal AI** integrating imaging, pathology, genomics and clinical data.
2) **Real-time adaptive radiotherapy** with automated contouring and replanning.
3) **Predictive radiotherapy** estimating individual tumour response and normal-tissue toxicity.
4) **AI-assisted tumour boards** synthesising complex clinical information.
5) **Digital twins** capable of modelling alternative treatment strategies.
6) **Continuous QA** detecting deviations across the treatment pathway.
7) **Federated learning**, allowing development of models across institutions while limiting centralisation of sensitive data.
8) **Natural-language interfaces** enabling clinicians to interact with planning and clinical systems conversationally.

The direction is therefore clear: AI is moving from a tool that performs a single task towards an **intelligent layer connecting the entire cancer-treatment pathway**.[4,5,22]

The successful department of the future may not be the one with the largest number of AI applications, but the one that integrates AI into clinical workflows **without compromising safety, accountability or the patient-doctor relationship**.

2. Conclusion

AI is poised to become an integral component of radiation oncology. Its greatest immediate impact will probably be through auto-contouring, image processing, treatment planning, adaptive radiotherapy and quality assurance, while radiomics, response prediction and multimodal clinical decision support remain areas of active development.

The radiation oncologist of the future will not need to choose between medicine and technology. The challenge will be to combine them.

AI should perform what machines do best—rapid computation, pattern recognition and optimisation—while clinicians retain what humans do best: contextual judgement, responsibility, communication and compassion.

The goal of AI should therefore not simply be to make radiation oncology faster.

The time saved by AI should become time returned to the patient.

AI may improve our plans, predict our outcomes and sharpen our decisions.

But AI cannot replace a caring heart and healing hands.

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