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Review Article

Improving performance in radiation oncology: An international systematic review of quality improvement interventions

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ABSTRACT

National cancer audits and registers have highlighted significant national and international variation in patient care and outcomes. Quality Improvement (QI) is mandated in radiation oncology but the interventions designed to support QI in this field remain poorly understood. This paper seeks to assess the types of QI interventions in radiation oncology, the QI evaluation design and their impact on process of care measures and patient-related outcomes. MEDLINE and EMBASE were searched systematically for studies of QI interventions in radiation oncology between 2000 and 2024. The studies needed to identify the quantitative or qualitative impact of the QI intervention on process of care measures or patient-related outcomes. Study results were summarised using narrative synthesis and appraised using the Quality Improvement Minimum Quality Criteria Set (QI-MQCS). 26 papers were included in the analysis. The majority of studies were conducted in the USA (n = 13) and in Europe (n = 7), with only two studies conducted at a national level. Ten studies covered all tumour types, with six specifically focusing on head and neck cancers, two each on prostate and nasopharyngeal cancers, and one study each examining lung, cervical, rectal, and breast cancers. The aspects of care evaluated most frequently were those relating to reducing waiting times or increasing utilisation of radiotherapy as per guidelines (n = 15), followed by those seeking to reduce radiotherapy contouring variability (n = 5) and those involving the management of symptoms during or after radiotherapy treatment (n = 6). Only 42 % of studies reported funding, with the most frequent funding source being national, government or federal (n = 6). All QI interventions across the 26 studies were successful as they resulted in an improvement in a process or patient-related outcome measure. The studies scored between 10 and 15 out of 16, according to the QI-MQCS criteria. Despite substantial investments in cancer research and development, there is a scarcity of information on how to enhance the quality of care in radiation oncology. While there are examples of national cancer audits and registers in a number of countries, much of the research in QI interventions is being conducted in the USA. This situation underscores the need for more comprehensive, well-funded studies and improved training for clinicians to conduct high-quality improvement activities and research. There should be a greater emphasis on the substantial gains that can be achieved by improving existing care in terms of access and outcomes, rather than solely focusing on innovation.

Introduction

There is growing recognition of the need to improve the quality of radiation oncology care. The essential steps in improving quality of care include measuring quality (quality assessment), identifying variation and its determinants (quality assurance), and implementing the appropriate pathway changes to address these variations (quality improvement) [1–3]. The final step, quality improvement (QI), has been defined as a set of techniques for the continuous study and enhancement of healthcare delivery to meet patients' needs and expectations [4].

Systematic reviews have identified various performance indicators used to assure the quality of radiation oncology care [5], and outcome

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reporting programs have been established to provide valuable data on variation [6]. However, there remains a critical gap in understanding which specific interventions can effectively improve care downstream and to what extent these can be translated across radiotherapy centres to improve quality of care at the population level. Previous systematic reviews of QI interventions have either explored a specific type of intervention (e.g. audit and feedback), across a range of different healthcare settings or interventions across all aspects of cancer care, including surgical and medical oncology [7]. However, a detailed understanding of other interventions undertaken locally in hospitals or as part of national interventions remains unaddressed.

To start to bridge this gap, this review identifies existing QI activities in radiation oncology; exploring the different aspects of care that the interventions address (e.g. contouring variability) and the types of interventions implemented to address these deficits. This work also evaluates the scale of the studies conducted in this field, for example whether these were national, regional or single centre interventions. In addition, we assess the methodological design of the studies, considering both the robustness of their methodology (e.g. use of comparator control arms) and the likelihood of interventions being transferable to other hospital contexts (e.g. through the inclusion of a linked theory of change). Additionally, we examine the impact of these interventions on care quality and their sources of funding.

Evidence aquistion

Study eligibility

This systematic review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) checklist and in accordance with a pre-specified protocol registered in the PROSPERO database (Registration Number: CRD42024579986). The protocol details the objectives, inclusion criteria, and methodological approach employed in this review. Studies were considered for inclusion if they examined the implementation of QI interventions in radiation oncology.

Search strategy

Search terms were designed to identify QI interventions/initiatives that specified a deficit in patient care within radiation oncology. Interventions could be implemented at the local (single hospital), regional (more than one hospital within a region) or national level. The study design included randomised controlled trials, non-randomised controlled trials and cohort studies. The detailed research strategy is provided in Appendix A. The review focused on studies published between 2000 and 2024 to ensure relevance to current QI interventions.

Publications were excluded if they were not written in English; involved patients with a haematological cancer type, patients younger than 18 years, or studies assessing interventions that did not involve the delivery of radiation oncological care following a diagnosis. Studies were excluded if they did not specify baseline data, such as data on the deficit prior to the intervention ('pre-intervention') or a parallel control cohort. This was essential to demonstrate that the quality improvement intervention effectively addressed the deficit by showing changes from before its introduction to after implementation. Additionally, studies were excluded if they lacked a process of care or patient-related outcome measure, focused solely on quality assessment or assurance (e.g., developing quality indicators or reporting outcomes of quality assurance programs) or only assessed adherence to QI interventions. Publications were also excluded if they were published as editorials, commentaries, letters, case reports, or in the "grey" literature.

A single author (JD) and a library Information Specialist conducted the electronic searches of EMBASE and MEDLINE databases via the OVID platform in November 2024. Titles and abstracts were reviewed by two authors (JD and GZ) to identify potentially relevant articles for full-text review. The final selection was independently performed by JD and GZ, with disagreements resolved through discussion with a senior author (AA). Publications excluded after the full-text review are listed in Appendix B.

Data extraction

Two authors (JD and GZ) extracted information on study characteristics, including article details (e.g. author, publication year, funding), the type of intervention and what aspect of care it addressed, population demographics, study methodology and key findings. The funding source was identified by explicit statements in the manuscript or acknowledgement section. The funding classification, based on prior research [8], was divided into Government (e.g., national government-level funding agency), Industry (e.g., pharmaceuticals), Philanthropic (any charitable organisations), Individual Cancer Centre (if funded by single cancer institute) and none stated. The description of the intervention and the quantitative or qualitative impact on patient-related outcomes or process of care measures were summarised.

The methods that were used for the quality improvement intervention were also documented. This could encompass temporary activities aimed at introducing potentially lasting organisational or structural changes, such as methods like Plan-Do-Study-Act (PDSA) cycles [9] or Lean methodology [10].

Study quality assessment

The Quality Improvement Minimum Quality Criteria Set (QI-MQCS) [11] was used to assess the quality of each study. The validated appraisal tool is designed to evaluate expert-endorsed QI domains applicable across a broad spectrum of QI studies. The QI-MQCS focuses on the quality of the design and translatability of the study, giving recognition to publications that assess and report on essential variables. The appraisal tool includes 16 items, with each study scoring between 0 and 16. A higher score indicates a lower risk of bias and superior study quality. Examples of the 16 domains include "organisational motivation" which details the organisational problem, reason, or motivation for the intervention, "adherence" which describes the adherence to the intervention through mechanisms that ensures compliance and "penetration" which identifies the reach of the intervention according to the number of units or sites participating in the intervention compared to the available / eligible units. Two authors (JD and AA) independently assessed each paper, and any score discrepancies were resolved through discussion.

Analysis of results

A narrative synthesis approach was used to analyse the studies [12]. All studies detailed the intervention and its outcomes. Due to the variation in study populations and intervention types, a *meta*-analysis was not conducted.

Evidence synthesis

Included studies

The electronic database searches identified 7632 studies. After screening titles and abstracts, 71 papers were selected for full-text review. Of these, 25 papers met the study eligibility criteria and 1 additional paper was added through hand searching [13]. The study selection process is illustrated in Fig. 1.

Study characteristics

Table 1 summarises the characteristics of the 26 publications. 13 studies from the USA [13–25], seven from Europe (the UK, the

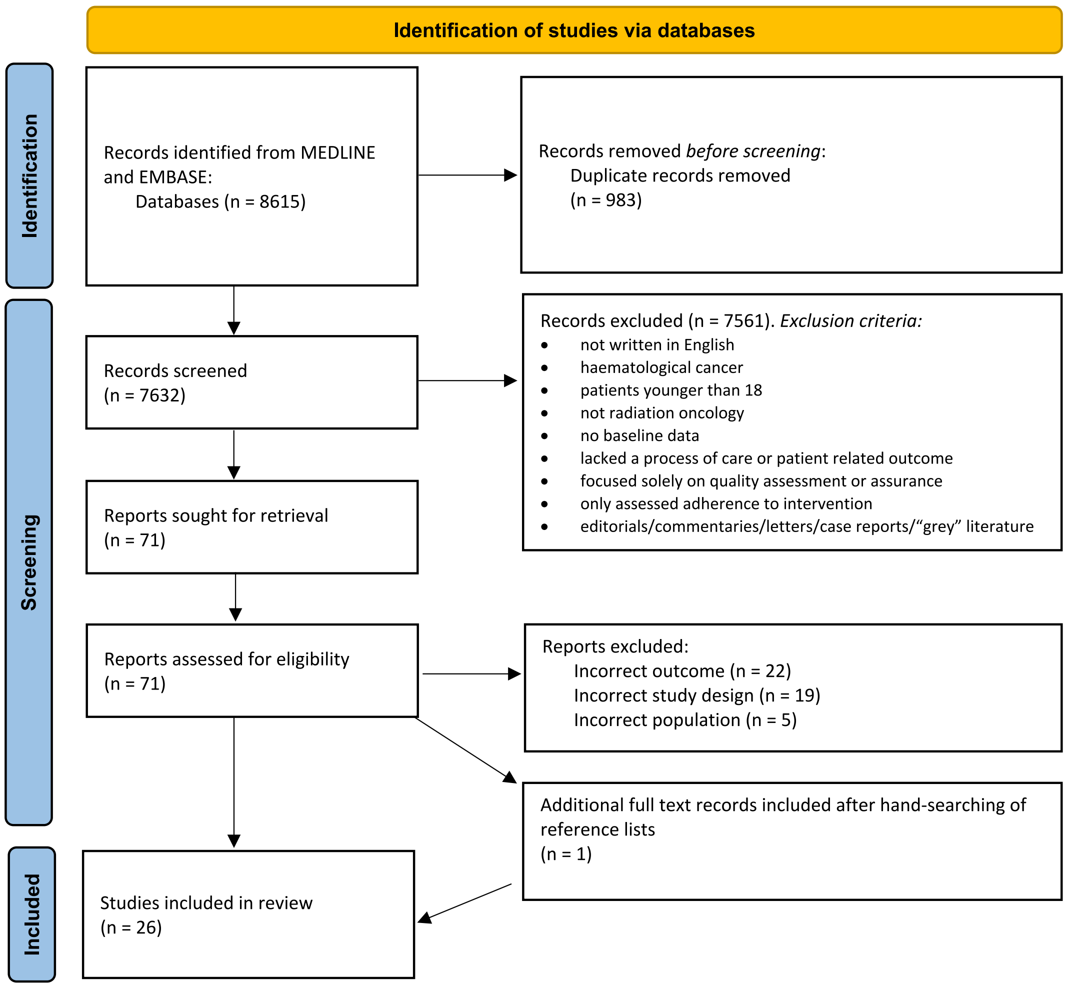

Fig. 1. PRISMA 2020 flow diagram of search strategy and study selection process [50].

Netherlands and Belgium) [26–32], three from Asia [33–35] and three from Australia [36–38]. Two studies were conducted nationally [27,29], three regionally [25,36,37] and 21 locally in a single centre [13–24,26,28,30–35,38]. Ten studies focused on all tumour types [13,15,19,23–25,31,32,35,38], six on head and neck [14,16,20,26,29,37], two on prostate [28,36], two on nasopharyngeal [33,34], one each on lung [30], cervical [21], rectal [27] and breast cancer [18] (see Fig. 2).

Eleven studies (42 %) reported funding [15,17,18,20,22,23,25,27,28,36,37], with six of these having multiple funding sources [15,18,25,27,36,37]. Most studies received funding from national government or federal sources (n = 6) [15,18,25,27,36,37]. Additionally, two studies were funded by philanthropic sources [23,28], two by industry [17,25], and two by individual cancer centres [20,22].

Type of quality deficit addressed

The most frequently evaluated aspects of care related to reducing waiting times (n = 12) [13,16,19,21,22,24,30–32,34,35,38] or increasing use of radiotherapy (n = 3) [15,25,36] (Table 2). This includes studies relating to referral rates to radiation oncology, waiting times for treatment, as well as uptake of evidence-based radiotherapy fractionation schedules. Other care aspects addressed included reducing radiotherapy contouring variability (n = 5) [23,26,27,29,33] and improving symptom management during or after radiotherapy treatment (n = 6) [14,17,18,20,28,37].

Study design and methodology

Table 2 details the study designs, the methodologies and outcomes. Most studies used a prospective observational design, with either a pre-intervention historical control [13–16,18–22,24,32–35], a parallel control [17,23,26,38] or time series [27,29–31]. Four studies were randomised control trials [25,28,36,37], with three using a stepped-wedge, cluster design [25,36,37]. Of these, three were conducted regionally and one locally. They investigated various quality deficits, including low uptake of short-course radiation for bony metastases [25], inadequate referral to radiation oncology after prostatectomy [36], increased malnutrition during head and neck radiotherapy [37], and poor symptom management during prostate radiotherapy [28].

With regard to QI methodologies five studies [14,16,21,22,32] used PDSA, two [13,30] used Lean methodology, two [33,35] using the clinical practice improvement (CPI) model [39], one [16] used the A3 framework (a form of lean methodology) [40] and one [21] used Pareto plot and process mapping [41].

Description of QI interventions

Table 2 describes the QI interventions used in each study. For reducing waiting times, interventions include same-day radiation oncology appointments [24], introducing additional "Day 0" appointments to ensure radiotherapy plans are ready in advance of first treatment [32], developing new referral pathways for palliative radiotherapy, such as being referred directly to the Palliative Advanced

Table 1
Key characteristics of studies selected for the systematic review.

Author (Year)	Ref	Title	Country	Unit (local/ regional/ national)	Cancer type	Cancer stage / RT intent	Sample size		Funding	Aspect of care addressed
							Patients	Centres		
Gillespie (2024)	[25]	Implementation Strategies to Promote Short-Course Radiation for Bone Metastases	USA	Regional	All	Metastatic	714	4	Pfizer/National Institutes of Health/National Cancer Institute	Poor uptake of short-course radiation for non-spine metastases
Chen (2023)	[24]	Effect of a Same-Day-Appointment Initiative on Access-Related Benchmarks in Radiation Oncology	USA	Local	All	All	4301	1	None	Long waiting times from referral to initial radiation oncology consultation
Gately (2023)	[32]	Reducing first appointment delays for electron radiotherapy patients by improving the treatment planning pathway: a quality improvement project	UK	Local	All	All	96	1	None	Long delays to the start of an appointment for radiotherapy
Gatfield (2022)	[26]	The impact of neuroradiology collaboration in head and neck cancer radiotherapy peer review	UK	Local	H&N	Radical	120	1	Funding not declared	Variability in target volumes and organs at risk contour delineation
Zhang (2022)	[23]	Prospective Clinical Evaluation of Integrating a Radiation Anatomist for Contouring in Routine Radiation Treatment Planning	USA	Local	All but prostate	All	249	1	Radiological Society of North America	Variability in quality of organ at risk contour delineation
Xu (2021)	[22]	Novel Inpatient Radiation Oncology Consult Service Model Reduces Hospital Length of Stay	USA	Local	Not specified	Metastatic	1252	1	MSK Cancer Center	Long waiting times for inpatient radiation oncology consults resulting in longer hospital stays
Bhatt (2020)	[14]	Improving thyroid function monitoring in head and neck cancer patients: A quality improvement study	USA	Local	H&N	RT to cervical region	254	1	Funding not declared	Poor thyroid function monitoring during radiotherapy
Goyal (2020)	[17]	Prospective Study of Use of Edmonton Symptom Assessment Scale Versus Routine Symptom Management	USA	Local	Not specified	All	255	1	Rowpar Pharmaceuticals	Poor symptom control during radiotherapy treatment
Mattes (2020)	[19]	Quality Improvement Initiative to Enhance Multidisciplinary Management of Malignant Extradural Spinal Cord Compression	USA	Local	All	RT for spinal cord compression	65	1	Funding not declared	Delayed referral to radiation oncology for radiotherapy to spinal cord compression
Vitzthum (2019)	[21]	Reducing prolonged chemo radiation treatment times for cervical cancer	USA	Local	Cervical	All	152	1	None	Prolonged total treatment times for chemoradition
Verbakel (2019)	[29]	Targeted Initiative to Improve the Quality of Head and Neck Radiation Therapy Treatment Planning in the Netherlands	Netherlands	National	H&N	All	Not specified	15	Funding not declared	Variability in organ at risk contour delineation

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Table 1 (*continued*)

Author (Year)	Ref	Title	Country	Unit (local/ regional/ national)	Cancer type	Cancer stage / RT intent	Sample size: Patients	Sample size: Centres	Funding	Aspect of care addressed
Brown (2018)	[36]	A multidisciplinary team-oriented initiative to increase guideline recommended care for high-risk prostate cancer	Australia	Regional	Prostate	High risk	1071	9	National Health and Medical Research Council /Prostate Cancer Foundation of Australia	Poor referral rates for radiotherapy within 4 months after prostatectomy
Ho (2018)	[33]	Implementation of temporal lobe contouring protocol in head and neck cancer radiotherapy planning: A quality improvement project	Singapore	Local	Nasopharyngeal	All	47	1	None	Variability in temporal lobe contour delineation
McCarter (2018)	[37]	Effectiveness of clinical practice change strategies in improving dietitian care for head and neck cancer patients according to evidence-based clinical guidelines	Australia	Regional	H&N	All	Not specified	4	National Health and Medical Research Council/ Hunter Cancer Research Alliance	Increased malnutrition during radiotherapy
Divi (2018)	[16]	Reducing the Time from Surgery to Adjuvant Radiation Therapy: An Institutional Quality Improvement Project	USA	Local	H&N	All	56	1	None	Increased waiting times for adjuvant radiotherapy after surgery
Chang (2018)	[15]	A Palliative Radiation Oncology Consult Service's Impact on Care of Advanced Cancer Patients	USA	Local	All	Advanced	450	1	National Institutes of Health/ National Palliative Care Research Center	Poor utilisation of single fraction palliative radiotherapy resulting in longer hospital stays
Lucas (2018)	[18]	Radiation Dermatitis: A Prevention Protocol for Patients With Breast Cancer	USA	Local	Breast	All	186	1	National Institutes of Health/ National Cancer Institute.	High rates of radiation dermatitis during radiotherapy
Simons (2017)	[30]	The effects of a lean transition on process times, patients and employees	Netherlands	Local	Lung	All	Not specified	1	Funding not declared	Delay between the first consultation and the first radiotherapy treatment
Terzo (2017)	[20]	Reducing Unplanned Admissions: Focusing on Hospital Admissions and Emergency Department Visits for Patients	USA	Local	H&N	All	97	1	University of North Carolina Institute for Healthcare Quality Improvement	Increased emergency and unplanned admissions due to symptoms during radiotherapy treatment
Job (2017)	[38]	Reducing radiotherapy waiting times for palliative patients: The role of the Advanced Practice Radiation Therapist	Australia	Local	All	Palliative	150	1	Funding not declared	Long waiting times from referral to radiation treatment
Goldfinch (2016)	[31]	The impact of the introduction of a palliative Macmillan consultant radiographer at one UK cancer centre	UK	Local	All	Palliative	184	1	Funding not declared	Reduced number of patients receiving palliative radiotherapy within 14 days
Joye (2014)	[27]	Does a central review platform improve the quality of radiotherapy for	Belgium	National	Rectal	All	1225	20	National Institute for Health and Disability Insurance/	Poor uniformity of contour delineation

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Table 1 (*continued*)

Author (Year)	Ref	Title	Country	Unit (local/ regional/ national)	Cancer type	Cancer stage / RT intent	Sample size: Patients	Sample size: Centres	Funding	Aspect of care addressed
		rectal cancer? Results of a national quality assurance project							Foundation against Cancer	
Lee C (2010)	[34]	Improving waiting times for radical radiotherapy treatment of nasopharyngeal cancer based on logistics re-engineering	Hong Kong	Local	Nasophargeal	Curative	177	1	Funding not declared	Long waiting times from diagnosis to radiation treatment
Kim (2007)	[13]	The Application of Lean Thinking to the Care of Patients With Bone and Brain Metastasis With Radiation Therapy	USA	Local	All	Metastatic	Not specified	1	Funding not declared	Long waiting times from referral to radiation treatment
Lee K (2007)	[35]	Metastatic spinal cord compression as an oncology emergency: getting our act together	Singapore	Local	All	Metastatic	39	1	Funding not declared	Delayed treatment from radiation oncology for spinal cord compression
Faithfull (2001)	[28]	Evaluation of nurse-led follow up for patients undergoing pelvic radiotherapy	UK	Local	Prostate and Bladder	Radical	115	1	Cancer Research Campaign	Poor symptom control during radiotherapy treatment

Key: H&N = Head and Neck; RT = radiotherapy.

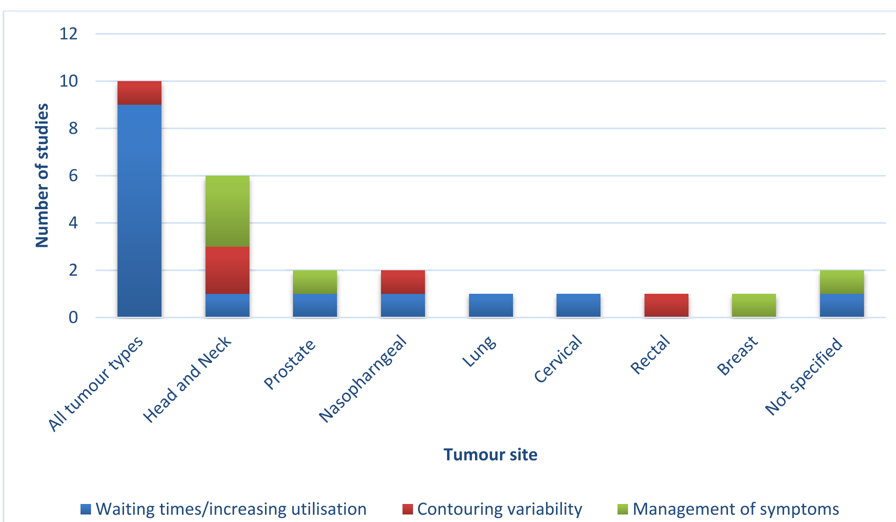

Fig. 2. Different tumour sites and the aspects of care evaluated by the QI intervention.

Practice Radiation Therapist [22,31,35,38] and process mapping to develop internal clinical pathways [13,16,19,21,30,34,35]. For QI studies aiming to increase the use of radiotherapy, interventions included establishing an inpatient radiation oncology consult services with expertise in palliative radiotherapy [15], personalised audit-and-feedback reports [25] and educational programs for staff [25,36].

To reduce contouring variability in head and neck, rectal and nasopharyngeal cancers, interventions involved appointing radiologists or radiation anatomists for radiotherapy planning [23,26], establishing central review facilities with consensus planning [27,29] and developing standardised contouring guidelines [33]. For managing symptoms during head and neck, breast, prostate and bladder radiotherapy, interventions included validated assessment tools for common symptoms [17,37], multi-disciplinary team clinics [20,28], symptom prevention protocols [18] and databases with patient monitoring alerts [14].

Outcomes of interventions

All studies reported improvements following the interventions, though not all showed statistically significant results, but this may be as a result of the small sample size of some studies. Among the 15 studies on reducing waiting times or increasing use of radiotherapy, all found improvements (e.g. median referral to consult time decreased from 12 to

Table 2
Description of study design, quality improvement intervention methodologies and outcomes.

Author (Year)	Ref	Title	Type of quality deficit	Study design*	Centres	Description of intervention	Outcome of intervention
Gillespie (2024)	[25]	Implementation Strategies to Promote Short-Course Radiation for Bone Metastases	Poor uptake of short-course radiation for non-spine metastases	Stepped-wedge, cluster randomised controlled trial	4	• Three implementation strategies were rolled out to physicians: • (1) dissemination of published consensus guidelines • (2) personalised audit-and-feedback reports • (3) an email-based electronic consultation platform (eConsult)	• Increased adjusted odds of adherence increased with calendar time (odds ratio, 1.68; P = 0.003). • No significant difference in unadjusted adherence rates (53 % vs 56 %, odds ratio, 0.78; P = 0.40)
Chen (2023)	[24]	Effect of a Same-Day-Appointment Initiative on Access-Related Benchmarks in Radiation Oncology	Long waiting times from referral to initial radiation oncology consultation	Pre-post prospective observational using historical control Pilot testing	1	• New patients referred for radiation oncology consultation were offered same-day appointments.	• Increased the proportion of patients seen within 5 days from referral from 22 % to 61 % (P < 0.001). • Reduced the median time from referral to consult from 12 days to 3 days (P < 0.001).
Gately (2023)	[32]	Reducing first appointment delays for electron radiotherapy patients by improving the treatment planning pathway: a quality improvement project	Long delays to the start of an appointment for radiotherapy	Pre-post prospective observational using historical control PDSA	1	• The treatment pathway for these patients was redesigned, by introducing: • (1) a proxy (without the patient present) 'day 0′ appointment. This takes place in advance of the radiotherapy appointment to enable earlier planning. • (2) automating previously manual planning calculations, • (3) making the care path consistent with other external beam radiotherapy care paths • (4) sharing key performance data with staff	• Improvement in number of appointments starting within 30 min of the appointment time (69.2 % vs 33 %).
Gatfield (2022)	[26]	The impact of neuroradiology collaboration in head and neck cancer radiotherapy peer review	Variability in target volumes and organs at risk contour delineation	Prospective observational cohort using parallel control	1	• A neuroradiologist joined the peer review team.	• Increase in change to plans when a neuroradiologist was present (55 % vs 33 %)
Zhang (2022)	[23]	Prospective Clinical Evaluation of Integrating a Radiation Anatomist for Contouring in Routine Radiation Treatment Planning	Variability in quality of organ at risk contour delineation	Prospective observational cohort using parallel control	1	• A radiation anatomist was trained and integrated into clinical practice. • Patients were assigned using an "every other" process to either (1) OAR contouring by a radiation anatomist (initiative) or (2) contouring by the treating physician (standard of care). • Blinded dosimetrists reported OAR contour quality using a 3-point scoring system based on a common clinical trial protocol deviation scale (1, acceptable; 2, minor deviation; and 3, major deviation).	• Improved mean OAR quality rating was (1.1 ± 0.4 vs 1.4 ± 0.7) (P < 0.001) • Reduced time from simulation to contour approval from 3 days to 2 days (P = 0.007).
Xu (2021)	[22]	Novel Inpatient Radiation Oncology Consult Service Model Reduces Hospital Length of Stay	Long waiting times for inpatient radiation oncology consults resulting in longer hospital stays	Pre-post prospective observational using historical control PDSA	1	• Created an inpatient radiation oncology consult service (IROC) with expertise in palliative radiation and ablative techniques. • Plans were reviewed in biweekly chart rounds by Radiation Oncologists with metastatic disease expertise.	• Decreased hospital length of stay (median 8 days v 7 days, P = 0.005).
Bhatt (2020)	[14]	Improving thyroid function monitoring in head and neck cancer patients: A quality improvement study	Poor thyroid function monitoring during radiotherapy	Pre-post prospective observational using historical control PDSA	1	• A dedicated database was established of all head and neck oncology patients who had completed radiotherapy. • Patients' thyroid function was tracked and documented at	• Increased compliance of thyroid monitoring from 34 % to 80 % (P < 0.0001).

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Table 2 (*continued*)

Author (Year)	Ref	Title	Type of quality deficit	Study design*	Centres	Description of intervention	Outcome of intervention
						six months and one year after treatment	
Goyal (2020)	[17]	Prospective Study of Use of Edmonton Symptom Assessment Scale Versus Routine Symptom Management	Poor symptom control during radiotherapy treatment	Prospective observational cohort using parallel control	1	• Initiative was initiated using the Edmonton Symptom Assessment Scale (ESAS). The ESAS is a 9-symptom validated self-assessment tool for reporting common symptoms in patients with cancer. • Patients were partitioned into 2 groups: (1) 85 patients completing weekly ESAS (preinitiative) but blinded to their providers who gave routine symptom management and (2) 170 completing weekly ESAS (post initiative group) reviewed by providers during weekly On treatment visits with possible initiative.	• Improved or stable symptom severity was seen for pain (70.7 % v 85.6 %; P = 0.005) and anxiety (79.3 % v 92.9 %; P = 0.002).
Mattes (2020)	[19]	Quality Improvement Initiative to Enhance Multidisciplinary Management of Malignant Extradural Spinal Cord Compression	Delayed referral to radiation oncology for radiotherapy to spinal cord compression	Pre-post prospective observational using historical control	1	• Development of an internal clinical pathway addressing delays in care. • Pathway included details on how to consult relevant physicians and expedite MRI and biopsy studies and their interpretations	• Decreased time from MRI spine to radiation oncology consultation from 3 to 1 days (P = 0.03).
Vitzthum (2019)	[21]	Reducing prolonged chemo radiation treatment times for cervical cancer	Prolonged total treatment times for chemoradition	Pre-post prospective observational using historical control PDSA Pareto plot and process mapping	1	• Process mapping identified inefficiencies with scheduling, staggered treatments and inadequate patient and staff education. • Institutional changes were implemented, utilising oncology nurses' skill set in staff re-education and care coordination. • The workflow was redesigned to reduce/eliminate treatment delays.	• Increased percentage of patients meeting the goal total treatment time (85.2 % vs 58.3 %, p < 0.01)
Verbakel (2019)	[29]	Targeted Initiative to Improve the Quality of Head and Neck Radiation Therapy Treatment Planning in the Netherlands	Variability in organ at risk contour delineation	Prospective observational time series	15	• A delineated computed tomography-scan of an oropharynx HNC case was sent to all 15 Dutch radiation therapy centres treating HNC. • Aims for planning target volume and organ-at-risk dosimetry were established by consensus. • Each centre generated a treatment plan. • In a targeted initiative, OAR sparing of all plans was discussed, and centres with the best OAR sparing shared their planning strategies.	• Reduced OAR mean doses; 18 Gy vs 22gy contralateral parotid gland; 28 Gy vs 35 Gy to contralateral submandibular gland; 29 Gy vs 37 Gy for combined swallowing structures.
Brown (2018)	[36]	A multidisciplinary team-oriented initiative to increase guideline recommended care for high-risk prostate cancer	Poor referral rates for radiotherapy within 4 months after prostatectomy	Stepped-wedge, cluster randomised controlled trial	9	• Interventions included flagging of high-risk patients by pathologists, clinical leader allocated, peer to peer education with dissemination of printed materials and quarterly audit and feedback of individuals' and study Sites' practices.	• Increased proportion of patients discussed at a MDT meeting from 17 % to 59 % (adjusted RR = 4.32; 95 % CI [2.40 to 7.75]; p < 0·001). • No significant difference in referral to radiation oncology (initiative 32 % vs control 30 %; adjusted RR = 1.06; 95 % CI [0.74 to 1.51]; p = 0.879).
Ho (2018)	[33]	Implementation of temporal lobe contouring protocol in head and neck cancer radiotherapy planning	Variability in temporal lobe contour delineation	Pre-post prospective observational using historical control Clinical Practice	1	• Development of a protocol to standardise temporal lobe contouring with a contouring atlas.	• Reduced variability in temporal lobe contouring from 39.9 % to 17.3 % (P = 0.004)

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Table 2 (*continued*)

Author (Year)	Ref	Title	Type of quality deficit	Study design*	Centres	Description of intervention	Outcome of intervention
				Improvement Program methodology			
McCarter (2018)	[37]	Effectiveness of clinical practice change strategies in improving dietitian care for head and neck cancer patients according to evidence-based clinical guidelines	Increased malnutrition during radiotherapy	Stepped-wedge, randomised controlled trial	4	• Development of 'Eating As Treatment' initiative where patients receive frequent contact with dietitians, dietitians use a validated nutrition assessment tool and patients at risk of depression are offered psychosocial support. • Audit and feedback and prompts used	• Improvement in monitoring weight, intake and nutritional status by 22 %.
Divi (2018)	[16]	Reducing the Time from Surgery to Adjuvant Radiation Therapy: An Institutional Quality Improvement Project	Increased waiting times for adjuvant radiotherapy after surgery	Pre-post prospective observational using historical control PDSA A3 framework	1	• Following process mapping, 12 interventions including earlier referral to a dentist, early referral to radiation oncology, a new co-ordinator role and weekly patient review rounds were established. Meetings were an opportunity to provide feedback to the quality improvement team to determine which interventions were being effectively implemented.	• Increased percentage of patients treated within 6 weeks from 62 % to 73 %.
Chang (2018)	[15]	A Palliative Radiation Oncology Consult Service's Impact on Care of Advanced Cancer Patients	Poor utilisation of single fraction palliative radiotherapy resulting in longer hospital stays	Pre-post prospective observational using historical control	1	• A Palliative Radiation Oncology Consult (PROC) service was established • Individual cases discussed on a regular basis during an associated specialty tumor board attended by PROC representatives.	• More patients had single-fraction radiation (RR: 7.74, 95 % CI: 3.84–15.57) and hypo fraction (2–5 fraction) radiation (RR: 10.74, 95 % CI: 5.82–19.83). • Shorter hospitals stays after initiative (21 vs. 26.5 median days, p = 0.01)
Lucas (2018)	[18]	Radiation Dermatitis: A Prevention Protocol for Patients With Breast Cancer	High rates of radiation dermatitis during radiotherapy	Pre-post prospective observational using historical control	1	• Developed a radiation dermatitis prevention protocol which included application of a mid- to high-potency steroid to the radiated field starting on day 1 of radiation therapy and continuing for two weeks after the last treatment.	• No patients had a grade 4 radiation dermatitis after implementation of protocol (vs 7 patients pre-initiative) • Increased adherence to RD prevention protocol from 7 % before implementation to 18 % after implementation (p = 0.046).
Simons (2017)	[30]	The effects of a lean transition on times, patients and employees	Delay between the first consultation and the first radiotherapy treatment	Pre-post Prospective observational cohort time series Lean methodology	1	• 15 lean interventions were initiated to improve flow including process redesign (i.e. consult and CT scan on same day)	• Improvement in time from first consultation to first radiotherapy treatment from 20.2 days to 16.3 days
Terzo (2017)	[20]	Reducing Unplanned Admissions: Focusing on Hospital Admissions and Emergency Department Visits for Patients	Increased emergency and unplanned admissions due to symptoms during radiotherapy treatment	Pre-post prospective observational using historical control	1	• A weekly nurse/nurse practitioner–led symptom management clinic was created for patients with head and neck cancer receiving radiation therapy deemed at high risk for an emergency (ED) visit or unplanned hospital admission (UHA).	• Reduced ED visit and UHA rates (11 % and 16 %, respectively) vs historic rates (18 % and 21 %, respectively). Not statistically significant.
Job (2017)	[38]	Reducing radiotherapy waiting times for palliative patients: The role of the Advanced Practice Radiation Therapist	Long waiting times from referral to radiation treatment	Prospective observational cohort using parallel control	1	• A new referral pathway was developed which involved patients requiring palliative radiotherapy being referred directly to the Palliative Advanced Practice Radiation Therapist. • Patients were stratified by method of referral i.e. via the new referral pathway or via standard referral pathway	• Significant reduction in the number of days from referral to treatment from mean wait time of 3.5 days compared to 8.1 days (P = <0.001)
Goldfinch (2016)	[31]	The impact of the introduction of a palliative Macmillan consultant	Reduced number of patients receiving palliative	Prospective observational time series	1	• A palliative radiotherapy consultant radiographer was appointed with autonomous	• Increase in patients treated within 14 days from 73 % to 85 %.

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Table 2 (*continued*)

Author (Year)	Ref	Title	Type of quality deficit	Study design*	Centres	Description of intervention	Outcome of intervention
		radiographer at one UK cancer centre	radiotherapy within 14 days			responsibility for palliative radiotherapy planning.	
Joye (2014)	[27]	Does a central review platform improve the quality of radiotherapy for rectal cancer? Results of a national quality assurance project	Poor uniformity of contour delineation	Prospective observational time series	20	• Central review facility was established and centres were asked to delineate the CTV of each rectal cancer patient. Delineation tools were distributed to all centres. • A radiation technologist was trained in CTV delineation and reviewed all cases. Delineations were reviewed within 24 h and, if necessary, the modified CTV was sent back to the original centre • Feedback on which CTV was finally used for treatment planning was reported	• There was a significant increase in agreement between the submitted CTV and modified CTV between the first ten patients per centre and the others (p < 0.001).
Lee C (2010)	[34]	Improving waiting times for radical radiotherapy treatment of nasopharyngeal cancer based on logistics re-engineering	Long waiting times from diagnosis to radiation treatment	Pre-post prospective observational using historical control	1	• Process redesign including earlier referral from regional ear, nose and throat departments upon endoscopic diagnosis of nasopharyngeal cancer, prioritising magnetic resonance imaging appointments and booking of workup procedures immediately upon receipt of a referral letter (i.e. before the first visit)	• Improvement in the waiting times for radiotherapy (diagnosis to treatment: 54 days vs. 38 days, p < 0.001).
Kim (2007)	[13]	The Application of Lean Thinking to the Care of Patients With Bone and Brain Metastasis With Radiation Therapy	Long waiting times from referral to radiation treatment	Pre-post prospective observational using historical control Lean methodology	1	• Lean methodology was used to improve flow including process redesign by establishing team representatives and designing a current and future value stream process map that allowed the delivery of radiotherapy faster, with fewer challenges and using fewer resources.	• Increase in the percentage of patients receiving consultation, simulation, and treatment within the same day from 43 % to 94 %. • Reduction in the number of individual process steps to begin treatment from 27 to 16.
Lee K (2007)	[35]	Metastatic spinal cord compression as an oncology emergency: getting our act together	Delayed treatment from radiation oncology for spinal cord compression	Pre-post prospective observational using historical control Clinical Practice Improvement Program methodology	1	• Interventions to form a multidisciplinary acute spinal cord crisis team, fine tune clinical referral processes and formulate a standardised treatment protocol were implemented.	• Improvement in the mean response time to start steroidal therapy from 8.4 to 2.6 days and radiotherapy from 9.9 to 3.9 days.
Faithfull (2001)	[28]	Evaluation of nurse-led follow up for patients undergoing pelvic radiotherapy	Poor symptom control during radiotherapy treatment	Randomised controlled trial	1	• A nurse–led symptom management clinic was created • The nurse provided leaflets on radiotherapy and how to manage symptoms during radiotherapy • Attendance at the nurse-led clinic was organised for within the first week and last week of radiotherapy.	• Improved symptom scores at week 1 between initiative and control groups i.e nocturia (P < 0.006), fatigue (P < 0.04), impact on activity from bladder symptoms (P < 0.01) and constipation (P < 0.001).

Study design extracted using the Quality Improvement Minimum Quality Criteria Set (QI-MQCS) user manual version 1.0 [ref].
Key: PDSA = Plan, Do, Study, Act; P = p value; CI = confidence interval; OR = odds ratio.

3 days, p=<0.001 [24]). A study that improved multidisciplinary team (MDT) discussion rates from 17 % to 59 % did not achieve the intended goal of increasing radiation oncology referrals for prostate cancer management (30 % to 32 %, p = 0.879 [36]).

In studies on radiotherapy contouring, all five demonstrated improvements (e.g. variability in temporal lobe contouring reduced from 39.9 % to 17.3 %, p = 0.004) [33]. In the six studies on symptom management, all reported improvements, such as increased thyroid monitoring compliance from 34 % to 80 % (p=<0.001) [14].

Study quality assessment

The quality of the studies assessed using the QI-MQCS criteria, was generally good, with scores ranging from 10 to 15 out of 16 (Table 3, Appendix C). All studies reported the domains like organisational motivation, rationale for the QI intervention and its description, study design, comparator, data source, and health outcomes. Fewer studies included organisation characteristics and penetration/reach (Table 3). Organisation characteristics, which relate to the demographics or basic

Table 3
Quality Improvement Minimum Quality Criteria Set (QI-MQCS) quality assessment.

			Quality Improvement Minimum Quality Criteria Set Domains																Total (row)
Author (Year)	Ref	Title	Organisational motivation	Initiative rationale	Initiative description	Organisation characteristic	Implementation	Study design	Comparator	Data source	Timing	Adherence/ fidelity	Health outcomes	Organisational readiness	Penetration/ reach	Sustainability	Spread	Limitations	
Gillespie (2024)	[25]	Implementation Strategies to Promote Short-Course Radiation for Bone Metastases	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	**15**
Chen (2023)	[24]	Effect of a Same-Day-Appointment Initiative on Access-Related Benchmarks in Radiation Oncology	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	**15**
Gately (2023)	[32]	Reducing first appointment delays for electron radiotherapy patients by improving the treatment planning pathway: a quality improvement project	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	**15**
Gatfield (2022)	[26]	The impact of neuroradiology collaboration in head and neck cancer radiotherapy peer review	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓	✓	**11**
Zhang (2022)	[23]	Prospective Clinical Evaluation of Integrating a Radiation Anatomist for Contouring in Routine Radiation	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	**14**
Xu (2021)	[22]	Novel Inpatient Radiation Oncology Consult Service Model Reduces Hospital Length of Stay	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		**13**
Bhatt (2020)	[14]	Improving thyroid function monitoring in head and neck	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	**13**

(*continued on next page*)

Table 3 (*continued*)

Author (Year)	Ref	Title	Quality Improvement Minimum Quality Criteria Set Domains: Organisational motivation	Initiative rationale	Initiative description	Organisation characteristic	Implementation	Study design	Comparator	Data source	Timing	Adherence/ fidelity	Health outcomes	Organisational readiness	Penetration/ reach	Sustainability	Spread	Limitations	Total (row)
		cancer patients: A quality improvement study																	
Goyal (2020)	[17]	Prospective Study of Use of Edmonton Symptom Assessment Scale Versus Routine Symptom Management	✓	✓	✓			✓	✓	✓	✓		✓	✓				✓	**10**
Mattes (2020)	[19]	Quality Improvement Initiative to Enhance Multidisciplinary Management of Malignant Extradural Spinal Cord	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓		✓	**13**
Vitzthum (2019)	[21]	Reducing prolonged chemo radiation treatment times for cervical cancer	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	**15**
Verbakel (2019)	[29]	Targeted Initiative to Improve the Quality of Head and Neck Radiation Therapy Treatment Planning	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	**14**
Brown (2018)	[36]	A multidisciplinary team-oriented initiative to increase guideline recommended care for high-risk	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	**14**
Ho (2018)	[33]	Implementation of temporal lobe contouring protocol in head and neck cancer radiotherapy planning	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	**14**
McCarter (2018)	[37]	Effectiveness of clinical practice change strategies	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	**14**

(*continued on next page*)

Table 3 (*continued*)

Author (Year)	Ref	Title	Quality Improvement Minimum Quality Criteria Set Domains																		Total (row)
			Organisational motivation	Initiative rationale	Initiative description	Organisation characteristic	Implementation	Study design	Comparator	Data source	Timing	Adherence/ fidelity	Health outcomes	Organisational readiness	Penetration/ reach	Sustainability	Spread	Limitations	
		in improving dietitian care for head and neck cancer patients																	
Divi (2018)	[16]	Reducing the Time from Surgery to Adjuvant Radiation Therapy: An Institutional Quality Improvement Project	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	**14**
Chang (2018)	[15]	A Palliative Radiation Oncology Consult Service's Impact on Care of Advanced Cancer Patients	✓	✓	✓	✓		✓	✓	✓	✓		✓				✓	✓	**11**
Lucas (2018)	[18]	Radiation Dermatitis: A Prevention Protocol for Patients With Breast Cancer	✓	✓	✓		✓	✓	✓	✓	✓		✓					✓	**10**
Simons (2017)	[30]	The effects of a lean transition on process times, patients and employees	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	**15**
Terzo (2017)	[20]	Reducing Unplanned Admissions: Focusing on Hospital Admissions and Emergency Department Visits for Patients	✓	✓	✓			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	**13**
Job (2017)	[38]	Reducing radiotherapy waiting times for palliative patients: The role of the Advanced Practice Radiation Therapist	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	**14**
Goldfinch (2016)	[31]	The impact of the introduction of a palliative	✓	✓	✓			✓	✓	✓	✓		✓	✓	✓	✓	✓		**12**

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Table 3 (*continued*)

Author (Year)	Ref	Title	Quality Improvement Minimum Quality Criteria Set Domains: Organisational motivation	Initiative rationale	Initiative description	Organisation characteristic	Implementation	Study design	Comparator	Data source	Timing	Adherence/ fidelity	Health outcomes	Organisational readiness	Penetration/ reach	Sustainability	Spread	Limitations	Total (row)
		Macmillan consultant radiographer at one UK cancer centre																	
Joye (2014)	[27]	Does a central review platform improve the quality of radiotherapy for rectal cancer? Results of a national quality assurance project	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**15**
Lee C (2010)	[34]	Improving waiting times for radical radiotherapy treatment of nasopharyngeal cancer based on logistics re-engineering	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓		✓	**13**
Kim (2007)	[13]	The Application of Lean Thinking to the Care of Patients With Bone and Brain Metastasis With Radiation Therapy	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	✓	**13**
Lee K (2007)	[35]	Metastatic spinal cord compression as an oncology emergency: getting our act together	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓				✓	**12**
Faithfull (2001)	[28]	Evaluation of nurse-led follow up for patients undergoing pelvic radiotherapy	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**14**
Total (column)			**26**	**26**	**26**	**13**	**20**	**26**	**26**	**26**	**25**	**16**	**26**	**22**	**11**	**17**	**16**	**24**	

characteristics of the organisation involved in the intervention (e.g. environment, type of care setting, size) and penetration or reach, which details the number of units or sites participating in the intervention compared to the eligible units, were missing in 13 and 11 studies respectively.

Discussion

In this systematic review of the published literature, we screened over 7,500 articles related to QI interventions in radiation oncology. However, only 26 relevant studies published between 2000 and 2024 were identified, with just five conducted at the regional or national level; the remaining studies were carried out at a single radiotherapy centre.

The primary finding of this review is the significant lack of published evidence on the use of QI interventions in radiation oncology. The existing research is largely concentrated in the USA and focused on head and neck (H&N) cancer, leaving QI interventions for other tumour types underexplored. While some studies have addressed key aspects of care including waiting times, and contouring there are considerable gaps in the literature, for example QI interventions to reduce rates of acute and late toxicity, or improve functional outcomes after treatment, which we know can be improved through quality assurance and improvement processes [42]. The two national studies reviewed focused on QI interventions aimed at reducing variability in radiotherapy contouring, while the three regional studies investigated interventions to increase utilisation of radiotherapy as per clinical practice guidelines or to manage symptoms during and after treatment.

The only comparable review was published in 2013 and focused on QI interventions targeting behaviour/practice changes in cancer specialists, not limited to radiotherapy alone [7]. That review identified only 12 studies across all domains of oncology and, of these, only one study explored radiation oncology care, specifically the underuse of specified best-practice treatments in breast and colon cancer [43]. Most interventions in that review incorporated a combination of audit and feedback, educational sessions, and involvement of opinion leaders. The study concluded there was a paucity of research in this area, and over 10 years later, our review shows that the published evidence on integrating QI interventions into everyday clinical practice remains scarce.

The first step to creating a QI culture is the need to assess and assure the quality of radiation oncology care and to use robust improvement science methodologies. However, without a systematic evaluation of quality, it becomes challenging to identify areas where existing practices could be improved. At present, a significant gap in this highly technical discipline is the absence of national quality assurance or audit programmes in radiation oncology [6]. An example of such monitoring interventions is the UK based National Cancer Audit Collaborating Centre, which enables all public sector cancer service providers in England and Wales to benchmark their outcomes against explicit standards, predefined quality improvement goals and other providers across 10 cancers [6,44]. Reporting performance against predefined and validated quality improvement goals and identifying areas where improvements are needed serves as a catalyst for healthcare providers to implement QI interventions aimed at addressing these variations in quality of care.

Other healthcare sectors have also recognised a shortage of published studies on QI interventions, suggesting that clinicians might lack the necessary time, skills or incentives to conduct and publish their improvement work [45]. The limited funding allocated to these types of studies further exacerbates the problem. In this review, all unfunded studies were conducted locally at individual radiotherapy centres, while most (80 %) of the regional and national studies received funding. This financial constraint results in a higher number of smaller-scale studies, which weakens the reliability and generalisability of the findings, making it challenging to apply the results to wider patient populations. However, this does not mean that these local QI interventions are not valuable. Due to variations between radiotherapy departments – such as differences in software, equipment, staffing, and workflows – some QI interventions may not be universally applicable across all settings, but can still have a positive impact on patient care.

Whilst randomised control trials (RCTs) are considered the gold standard, their high cost and time requirements may limit their practicability in this context. The shortage of published work could also stem from uncertainty about how to effectively report whether an intervention has succeeded. Radiation oncology teams aiming to conduct and evaluate QI interventions should be encouraged to use standardised measures and methods, which would address concerns about replicability. To facilitate this, guidelines have been developed to provide authors with a detailed checklist to ensure adequate data reporting of QI interventions [46]. Clear reporting on contextual factors and the specific components of an intervention would also help other healthcare systems implement similar interventions. In addition, educational courses have been developed within the ESTRO school which encourage a deeper dive into quality assurance and improvement within radiation oncology [47]. We note, 14 out of 26 studies were pre-post prospective observational studies using historical controls only. As a result, many studies did not adequately control for pre- and post-intervention outcomes, raising concerns about the methodological rigor of these interventions and consequently, the validity of their findings.

This review highlights several well-designed studies that could serve as valuable references for others, depending on the identified quality gaps. Long waiting times are a longstanding issue within oncological care. The Simons study [30], which utilised lean methodology, addressed this issue effectively. It introduced 15 interventions aimed at improving patient flow, including a process redesign that allowed for a consultation and CT scan to occur on same day. These changes led to a 20 % reduction in time from the initial consultation to the start of radiotherapy. Another example is a central peer review process being implemented, as demonstrated by Joye et al [27], who showed that such an approach could be adopted on a national scale. This intervention involved the creation of a central review facility where clinical tumour volume (CTV) delineations for each rectal cancer patient were submitted, reviewed and modified if necessary. As a result, three-quarters of all CTVs were adjusted and communicated with the treating centres. This national-level intervention aimed at standardising radiotherapy delineations could be adopted by other centres. Both of these studies emphasise the importance of organisational readiness and behavioural change to ensure successful implementation of QI interventions [48].

Strengths and limitations

This study's strengths include its inclusion of international publications identifying QI interventions and their impact on clinical outcomes in radiation oncology. However, a limitation is that we did not account for statistical uncertainty in the published clinical outcome results when summarising findings across studies. All studies were conducted in high-income countries (USA, UK, Singapore and Australia), with 13 based in the US, which may influence patient outcomes in ways specific to those health systems.

We could only identify 26 studies which is a small number given that we included studies published over a time window of more than 20 years. Furthermore, all studies in this review reported benefits to clinical outcomes, which is important given past concerns that publications on QI interventions are scarce due to publication bias and clinicians' reluctance to publish studies with 'negative' results [49]. Finally, reports not published as peer—reviewed research papers published (i.e. "grey literature" were excluded due to their diverse, non-traditional format, which is challenging to review systematically). This exclusion emphasises the difficulty in accessing comprehensive information on QI interventions in radiation oncology.

Conclusion

Despite significant investments in cancer research and development, there is a lack of information on how to improve the quality of care in radiation oncology. Of the small number of studies found, the main focus to date is waiting times, increasing rates of utilisation, symptom management and contouring variability, many of which had methodological limitations. This highlights the need for more comprehensive, well-funded studies that adhere to established standard reporting guidelines, as well as better training for clinicians to carry out high-quality improvement activities and research. Greater emphasis should be placed on the substantial gains that can be made by enhancing existing care in terms of access and outcomes, rather than focusing exclusively on innovation.

CRediT authorship contribution statement

Joanna Dodkins: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Georgia Zachou:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adil Rashid:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Jan van der Meulen:** Writing – review & editing, Validation, Supervision. **Julie Nossiter:** Writing – review & editing. **Alison Tree:** Writing – review & editing. **Ajay Aggarwal:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radonc.2025.110798.

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