Review

Patient Safety in Radiotherapy: Human Factors and Error Prevention Systems

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Citation: Žarkovič L , Zupan I, Hankić L, Žager Marciuš, Gošnak Dahmane R. Patient Safety in Radiotherapy: Human Factors and Error Prevention Systems. Proceedings of Socratic Lectures. **2026**, 14, 25-31. https://doi.org/10.55295/PSL.14.2026.I4

Abstract:
Radiotherapy is a cornerstone of modern cancer treatment, offering high precision in tumor targeting while minimizing damage to surrounding healthy tissues. Due to the use of high-energy ionizing radiation and highly complex planning and delivery workflows, patient safety represents a critical aspect of radiotherapy practice. This review provides an overview of patient safety in radiotherapy with a particular focus on human factors, sources of error, and system-based error prevention strategies. A narrative literature review was conducted using peer-reviewed articles, international guidelines, and reports on incident learning systems and quality assurance in external beam radiotherapy. The radiotherapy process consists of multiple interdependent stages, including simulation, target delineation, treatment planning, verification, and treatment delivery, each of which carries specific safety risks. Evidence shows that most radiotherapy incidents arise from human and organizational factors such as communication failures, workload, inadequate supervision, and system design issues rather than isolated technical faults. Quality assurance programs, incident reporting systems, patient safety indicators, and international frameworks such as Safety in Radiation Oncology (SAFRON) represent key mechanisms for preventing errors. The integration of technical quality assurance with a strong safety culture and attention to human factors is essential for reducing risk and improving patient outcomes. A system-based approach that emphasizes learning, supervision, and continuous improvement is crucial for maintaining safe radiotherapy practice as treatment technologies continue to evolve.

Keywords: Radiotherapy; Patient safety; Human factors; Quality assurance; Incident learning systems; Safety culture

1. Introduction

Radiotherapy is one of the three main pillars of modern cancer treatment, alongside surgery and systemic therapies. It is indicated for a large proportion of cancer patients during their treatment. This treatment can precisely target malignant tissue while sparing surrounding healthy structures. As a result, radiotherapy plays a crucial role in both curative and palliative oncology. However, the use of high-energy ionizing radiation, combined with complex planning and delivery processes, means that even small deviations can result in significant patient harm. For this reason, patient safety is considered a central component of quality radiotherapy practice.

A typical radiotherapy workflow consists of several interconnected stages. These include patient consultation, preparation on the simulator (usually CT imaging), target and organ-at-risk delineation, treatment planning, plan verification and quality assurance, treatment delivery, and ongoing verification throughout the treatment course. Each step requires close collaboration between radiation oncologists, medical physicists, and radiation therapists (RTTs) in the radiotherapy department. Radiotherapy irradiation techniques such as intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) have become increasingly advanced. Imaging verification methods, including image-guided radiotherapy (IGRT) and surface-guided radiotherapy (SGRT), further enhance treatment accuracy. In addition, adaptive radiotherapy (ART) has emerged as a novel approach that enables treatment adaptation during the course of therapy. These advances increase the number of parameters and decision points in the radiotherapy workflow, offering clinical benefits while also introducing additional complexity and potential risk.

As technology develops, the risk of errors increases. These errors are not only related to equipment and software but also to human performance. Human factors, including communication failures, workload, fatigue, inadequate supervision, and system design issues, are now recognized as major contributors to safety events in radiotherapy. Importantly, most radiotherapy incidents do not arise from a single catastrophic failure. Instead, they come from a chain of small deviations that go undetected across multiple stages of the process. Understanding these risks is key to building better safety measures.

The aim of this review is to provide an overview of patient safety in radiotherapy with a specific focus on human factors, common sources of error, and modern systems for error prevention. By examining recent literature on incident reporting, safety culture, and quality assurance mechanisms, this paper highlights strategies that support safer radiotherapy practice and reduce the likelihood of harm to patients.

2. Radiotherapy Principles and Technology

Modern radiotherapy aims to maximize tumor control while delivering the lowest possible dose to surrounding normal tissues (with minimal toxicity). This is achieved through accurate dose delivery and high spatial precision. Advanced irradiation techniques, such as IMRT and VMAT, and imaging verification methods such as IGRT and SGRT, shape and adjust the beam intensity to match the tumor's form. These methods allow the radiation dose to conform closely to the target, reducing exposure to healthy organs. High-energy radiation causes direct and indirect Deoxyribonucleic acid (DNA) damage in cancer cells, which are more sensitive than healthy cells (Hall & Giaccia, 2019). This leads to cell death or loss of reproductive ability in the tumor while trying to protect normal tissue as much as possible.

Although these technologies greatly improve treatment results, they also add more complexity. The increased number of steps and variables makes the process more vulnerable to errors. This complexity must be carefully managed to ensure patient safety (Krauss et al., 2023).

3. Workflow of a Typical Radiotherapy Process

Radiotherapy treatment involves a sequence of steps that depend on each other (Krauss et al., 2023). Each step has specific safety risks if performed incorrectly. The process starts with Computed Tomography (CT) simulation, where the patient is positioned reproducibly using immobilization devices. Accurate patient positioning and imaging are essential

because setup and intrafraction positioning errors may compromise target coverage and increase radiation exposure to surrounding healthy tissues (Barnes et al., 2020).
After simulation, the radiation oncologist outlines the target areas and organs to avoid. This step depends on the doctor's experience and reading images, so it can have variations or thinking errors (Boulanger et al., 2021). Then, medical physicists or dosimetrists make the treatment plan. They adjust the dose to match the doctor's goals and limits. Modern planning tools are complex, so independent checks and quality assurance are needed to find errors (Krauss et al., 2023). These checks help catch problems early.
Before delivering treatment, the plan undergoes technical and clinical checks. This includes dose calculations, machine settings, and final approval. During delivery, RTTs play a critical role in ensuring patient safety by performing patient identification (ID – patient identification which represents the process of confirming that the correct patient is receiving the correct treatment plan through verification of at least two independent identifiers such as the patient's name and date of birth and comparision with treatment documentation and information systems) and patient setup. Patient setup refers to the precise positioning of the patient on the treatment couch according to the position defined during CT simulation, using immobilization devices, laser alignment and predefined coordinates. Image-guided verification is routinely used to confirm the position before each irradiation of the patient. Any problems in communication, supervision, or adherence to protocols can put patient safety at risk. Good teamwork and clear procedures are essential at every stage. The complexity and interdependence of these stages are illustrated in **Figure 1**, which highlights key points in the workflow, where safety risks and potential errors may occur.

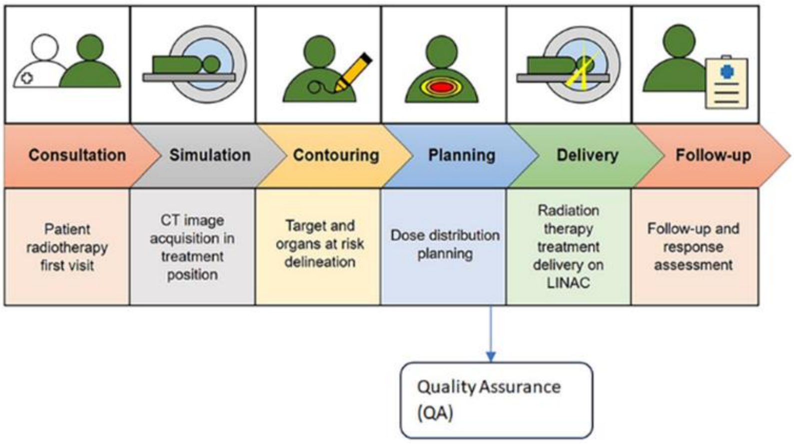

Figure 1. Typical workflow of external beam radiotherapy with key stages where safety risks and potential errors may occur. CT = computed tomography; LINAC = linear accelerator. From (Marvaso et al., 2022, CCBY 4.0 License).

4. Human Factors and Sources of Error in Radiotherapy

Human factors play a key role in safety events in radiotherapy. This is due to the complex, multidisciplinary, and technology-intensive nature of the treatment process. Modern radiotherapy workflows involve constant interaction between staff and advanced systems. This makes them highly sensitive to cognitive, organizational, and supervisory factors. Recent studies show that most incidents result not only from technical issues but from the interplay between human performance and system design (Weintraub et al., 2021; He et al., 2024).
Analyses of incident databases using the Human Factors Analysis and Classification System (HFACS) reveal that errors arise at multiple system levels. Weintraub et al. (2021) found that safety events are often linked to skill-based errors, decision-making errors, and perceptual errors at the operational level. However, these active errors are typically preceded by latent conditions, such as inadequate supervision, insufficient training, or unclear procedures. Supervision failures – for example, limited oversight during treatment planning or incomplete verification of plan changes – significantly increase the risk of errors reaching the patient. He et al. (2024) further examined organizational and supervisory factors using HFACS combined with Bayesian network

analysis. Their results indicate that organizational climate, safety management practices, and supervisory processes have a strong indirect impact on unsafe actions. Key contributors include staffing shortages, time pressure, and inconsistent protocol enforcement, which weaken protective barriers. These findings support the view that radiotherapy safety is mainly a systems-level issue rather than a matter of individual performance. The relationship between active errors and latent organizational conditions in radiotherapy incidents is summarized in **Figure 2.**

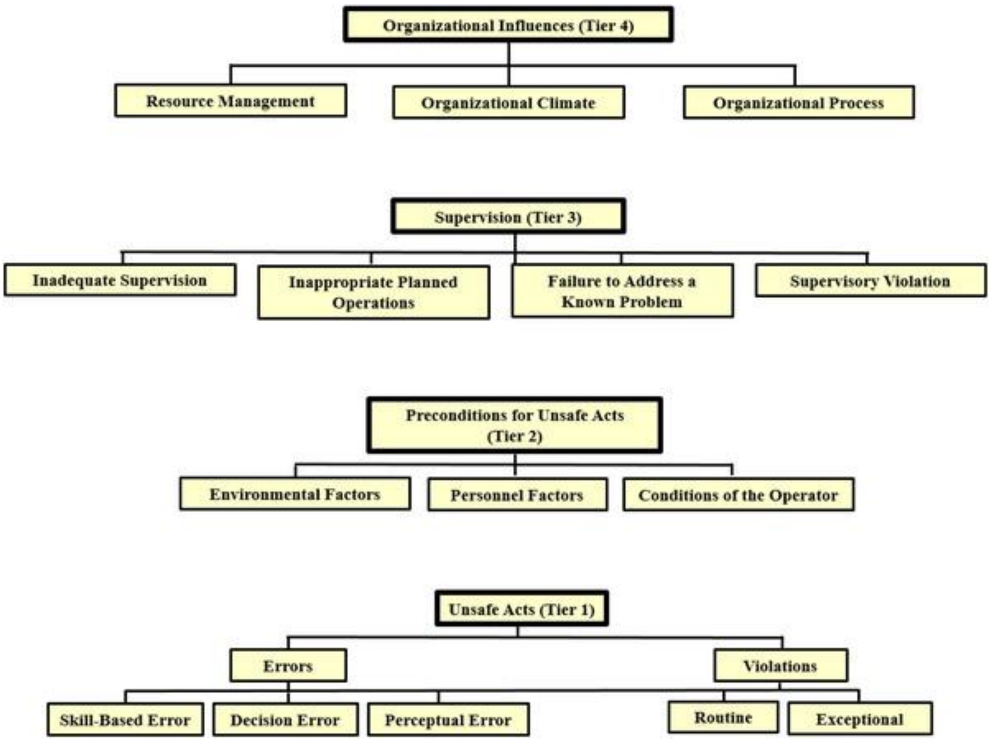

Figure 2: Application of the Human Factors Analysis and Classification System (HFACS) to radiotherapy safety incidents, illustrating the interaction between organizational, supervisory, and operational factors. From (Weintraub et al., 2021, CCBY 4.0 License).

5. Error Prevention Systems in Radiotherapy

Because radiotherapy errors have many causes, today's safety methods use several layers of protection. Quality assurance programs are the main way to stop errors. They include putting new machines into use (commissioning), regular equipment checks, independent dose verification, and peer review of treatment plans. Standard rules and checklists are used more and more to make sure everyone does things the same way. These layers help catch problems at different points. Incident reporting and learning systems are another very important part of patient safety. These systems let departments collect, study, and learn from real accidents and near-misses. Proof shows that when people are not punished for reporting, they tell the truth more often and safety gets much better. What we learn from these reports can be used to change work steps, give better training, and improve supervision (Zarei et al., 2023).

New digital tools make safety even stronger. Electronic checklists, automatic plan checking tools, and record-and-verify systems help people remember less and write less by hand. When safety checks are built straight into the daily work, these tools find problems before they reach the patient (Lastrucci et al., 2024; Mulla et al., 2025).

6. Patient Safety Indicators and Incident Learning Systems

In response to the need for measurable and standardized safety frameworks, patient safety indicators (PSIs) have been proposed as a structured way to monitor and improve radiotherapy processes. Baehr et al. (2025) carried out a comprehensive systematic review as part of the PaSaGeRO study. They identified and categorized 145 PSIs relevant to radiation oncology. These indicators cover several areas, including treatment planning accuracy, patient identification, equipment performance, human factors, and organizational processes

(Baehr et al., 2025). The review shows that PSIs linked to human performance and workflow organization are among the most frequently reported and clinically important. Indicators such as deviations from standard procedures, communication problems, and lack of independent checks are often associated with higher risk of adverse events. By adding PSIs to routine quality management systems, departments can spot trends, find weak points in the process, and apply targeted fixes before errors cause harm to patients (Baehr et al., 2025). Incident reporting and learning systems are a key part of modern radiotherapy safety management. Crouch et al. (2025) studied a 12-month use of an incident learning system in a radiotherapy department. They found a clear increase in reported near-miss events and better staff involvement in safety practices. The study stresses that more reports do not mean safety is getting worse – it means a better safety culture with openness and shared responsibility. Safety culture is closely connected to support from supervisors and leadership. A study in a radiotherapy department in Malta looked at patient safety culture and communication (Bezzina & Morone, 2025). It highlighted the value of supportive supervision and management commitment. Staff who felt supported by supervisors were more willing to report incidents and raise concerns about risks (Bezzina & Morone, 2025). These results match HFACS-based research, which points to supervision and organization as key areas for safety improvement.

7. International Safety Frameworks and Incident Learning Systems

The Safety in Radiation Oncology (SAFRON) system, supported by the International Atomic Energy Agency (IAEA), is an important step forward in understanding and preventing safety incidents in external beam radiotherapy. SAFRON is a full platform for reporting and learning from incidents. It lets departments around the world share anonymized events, study causes, and apply prevention strategies from shared knowledge. The system focuses on incidents in the full EBRT workflow, from planning to delivery with linear accelerators, IMRT, and VMAT. Reports to SAFRON show common patterns that point to weak spots in the process. Technical faults are important but make up only a small part of incidents. Most safety events come from communication problems, poor verification steps, or not following protocols in key stages like plan approval or patient positioning. This shows that external beam radiotherapy (EBRT) safety depends not just on reliable equipment but on good organizational systems and human performance in complex workflows. SAFRON data prove that many incidents can be prevented with strong safety barriers. These barriers act as checkpoints to catch and stop errors before they move to the next step. Examples are independent dose calculations, peer review of plans, pre-treatment imaging checks, and automatic checks in record-and-verify systems. When several barriers are well set up and always used, they add redundancy and greatly lower the chance of patient harm. However, barriers often fail when time pressure, staffing limits, or poor training reduce how carefully checks are done. SAFRON stresses learning from both real incidents and near-misses. Near-misses – errors caught before reaching the patient – give useful chances for improvement without harm. Departments with strong safety cultures encourage near-miss reporting and use it to fix weak processes. Regular analysis of incident causes in SAFRON has helped create targeted actions, including standard protocols, better training, and technology to reduce manual checks.

8. Quality Assurance Standards and Technical Safety Measures in External Beam Radiotherapy

EBRT is the most common form of radiation treatment. It uses high-energy beams from medical linear accelerators to target cancer tissue. The complexity of linear accelerator technology, together with advanced planning systems and irradiation techniques like IMRT and VMAT, requires strict quality assurance protocols to keep patients safe. Quality assurance (QA) in radiotherapy includes planned activities to make sure equipment meets standards, treatment plans are delivered correctly, and possible errors are found and fixed before they affect the patient. The value of full quality assurance programs has been supported by international safety efforts and professional guidelines. These frameworks stress that technical safety measures must work together with human factors approaches to build strong systems that stop errors at many levels. This section reviews established quality assurance standards, technical requirements for linear accelerators, incident learning systems for external beam radiotherapy, and how these are used in daily practice.

9. Integration of Quality Assurance with Human Factors and Safety Culture

Technical quality assurance protocols are vital, but their success depends on how people apply them in the organization. Studies using the Human Factors Analysis and Classification System (HFACS) with Bayesian network modeling show that organizational climate and supervision strongly affect quality assurance failures. Short staffing, uneven protocol enforcement, and time pressure can lead to shortcuts in QA, creating risks that technology alone cannot fix. The HFACS-Bayesian approach shows links between hidden organizational conditions and direct failures in treatment. For example, departments that give little time for QA or push for high patient numbers over careful work raise the risk of missed checks. Poor training on QA tools or lack of supervision to check skills can make even good protocols ineffective. These results show that lasting safety in external beam radiotherapy needs combined technical and organizational methods. Quality assurance programs must have leadership support, enough resources, and a culture that values careful work over speed. Surveys of safety culture in radiation oncology confirm that organizational commitment to safety is a key determinant of QA adherence and reporting behavior (Sharma et al., 2022). Staff should feel safe to report quality concerns without punishment, and enough time must be given for proper checks. When organization supports strict QA, technical steps become much better at stopping errors from reaching patients.

10. Discussion

Patient safety in radiotherapy is fundamentally shaped by the interaction between complex technology, human performance, and organizational systems. As demonstrated throughout this review, modern radiotherapy irradiation techniques such as IMRT, VMAT, as well as image verification methods like IGRT and SGRT have significantly improved treatment precision and clinical outcomes, yet they have simultaneously increased procedural complexity. This complexity creates multiple points at which errors can occur, particularly when workflows rely heavily on human decision-making, communication, and supervision. A consistent finding across the reviewed literature is that radiotherapy incidents are rarely the result of single technical failures. Instead, they emerge from combinations of human factors and latent system weaknesses. Factors such as high cognitive workload, time pressure, fatigue, insufficient training, and unclear protocols contribute substantially to unsafe actions during planning, verification, and treatment delivery. Analyses using the Human Factors Analysis and Classification System (HFACS) highlight that organizational and supervisory failures often precede active errors at the operational level. These findings reinforce the need to shift from individual blame toward a systems-based understanding of safety. QA remains the primary technical safeguard in external beam radiotherapy. Comprehensive QA programs for linear accelerators, including commissioning, routine performance testing, and imaging verification, are essential for ensuring accurate dose delivery and geometric precision. However, evidence indicates that technical safeguards alone are insufficient if organizational conditions undermine their consistent application. Time constraints, staffing shortages, and weak safety culture can reduce the effectiveness of even well-designed QA protocols. Incident learning systems, such as SAFRON, play a central role in identifying recurring risk patterns and strengthening safety barriers. The emphasis on reporting near-miss events is particularly valuable, as it enables learning without patient harm. Departments that foster non-punitive reporting environments demonstrate higher reporting rates and stronger engagement in safety improvement. Patient safety indicators further support proactive risk management by allowing systematic monitoring of workflow performance and human-factor-related vulnerabilities. Ultimately, sustainable improvements in radiotherapy safety depend on the integration of technical standards with organizational commitment and a strong safety culture. Leadership support, adequate resources, structured supervision, and continuous education are critical for ensuring that safety measures are effectively implemented in daily practice. As radiotherapy technologies continue to advance, the importance of combining human factors approaches with robust quality assurance frameworks will only increase. A proactive, system-based approach focused on learning and continuous improvement remains essential for minimizing patient harm and ensuring high-quality radiotherapy care.

11. Conclusions

Radiotherapy is a highly complex treatment where patient safety depends on how human performance, organization, and technology work together. Recent evidence shows human factors – especially supervision and organizational conditions – are major causes of safety events. System-based methods, including patient safety indicators and incident learning systems, provide effective ways to prevent errors. Full quality assurance standards for radiotherapy, backed by frameworks like SAFRON and AAPM guidelines, give essential technical protection that works with human factors approaches. Linear accelerator QA ensures reliable equipment and accurate treatment, while incident learning helps find weak processes and make improvements. But technical measures work best when supported by cultures that put safety first, provide resources, and encourage careful checks. Modern radiotherapy safety frameworks focus on strong systems, good supervision, and solid safety culture rather than blaming individuals. Combining strict technical standards with attention to human and organizational factors is the most promising way to keep patients safe as techniques become more advanced. Ongoing research and targeted actions in these areas are needed for safe, high-quality radiotherapy care.

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