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Review Article

Advancements in Imaging-Guided Radiotherapy for Enhancing Precision and Treatment Outcomes in Patients With Solid Tumors

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ABSTRACT

Background: Image-guided radiotherapy (IGRT) has evolved from planar verification and cone-beam computed tomography toward surface guidance, real-time motion management, magnetic resonance-guided radiotherapy, online adaptive planning, functional imaging, and artificial intelligence-supported workflows. Although these technologies improve geometric and dosimetric precision, uncertainty remains regarding the extent to which increasing technological complexity translates into superior long-term clinical outcomes and value across solid tumors. Objective: To narratively synthesize contemporary evidence on the role of advanced IGRT technologies in improving treatment precision, normal-tissue sparing, motion management, adaptive delivery, and clinical outcomes in patients with solid tumors, while critically evaluating limitations and implementation barriers. Methods: A narrative evidence synthesis was undertaken using 24 supplied peer-reviewed clinical studies, randomized and observational investigations, technical reports, disease-specific reviews, systematic reviews, and expert syntheses addressing conventional and emerging IGRT modalities. Evidence was organized thematically according to volumetric verification, motion management, surface guidance, MR-guided and online adaptive radiotherapy, functional imaging, and automation. Clinical outcome evidence was interpreted separately from technical and dosimetric evidence, with attention to study design, follow-up, comparator quality, patient selection, and translational limitations. Results: The most consistent evidence supported improved target localization, management of anatomical variation and motion, adaptive feasibility, and organ-at-risk sparing. MR-guided online adaptation showed particular promise for mobile or poorly visualized tumors near critical structures, although randomized comparative evidence remained limited to selected indications. Evidence for universal improvements in survival, long-term disease control, and cost-effectiveness was substantially less mature than evidence for geometric and dosimetric benefit. Conclusion: Advanced IGRT should be deployed according to clinical complexity and treatment uncertainty rather than technological availability alone. Multicenter comparative trials, standardized endpoints, longer follow-up, economic evaluation, and validated automated workflows are needed to establish where technical precision produces meaningful patient benefit. Keywords: Image-Guided Radiotherapy; Adaptive Radiotherapy; Magnetic Resonance Imaging; Cone-Beam Computed Tomography; Stereotactic Body Radiotherapy; Motion Management; Artificial Intelligence; Solid Tumors.

INTRODUCTION

Radiotherapy remains a fundamental component of multidisciplinary cancer care and is used across a broad spectrum of solid malignancies. Its therapeutic effectiveness depends on delivering an adequate radiation dose to

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the intended target while minimizing exposure to surrounding organs at risk. This balance is particularly challenging when tumors are located adjacent to radiosensitive structures or are affected by physiological motion and day-to-day anatomical variation. Conventional two-dimensional and early three-dimensional treatment approaches relied heavily on bony landmarks and population-based safety margins to compensate for uncertainties in patient positioning and internal anatomy. Although these margins reduced the likelihood of geographic target miss, they also increased irradiation of normal tissues and constrained opportunities for safe dose escalation. The progressive integration of image-guided radiotherapy (IGRT) has therefore become central to improving geometric accuracy and treatment conformity in contemporary radiation oncology (1,2).

IGRT encompasses a range of technologies that provide imaging immediately before or during treatment to verify patient positioning, characterize internal anatomy, and support correction of geometric deviations. Planar kilovoltage and megavoltage imaging established the foundation for treatment verification, whereas cone-beam computed tomography (CBCT) subsequently enabled three-dimensional assessment of target and organ position at the treatment unit. These developments have improved the management of interfractional variations arising from differences in bladder or rectal filling, weight change, tumor regression, and other anatomical alterations during a radiotherapy course (2,3). More recently, surface-guided radiation therapy (SGRT), respiratory motion-management strategies, stereotactic techniques, and real-time tracking systems have further expanded the capacity to control treatment uncertainty, particularly in anatomical regions affected by respiratory and other intrafractional motion (3,4).

Despite these advances, conventional image guidance remains subject to important limitations. X-ray-based volumetric imaging may provide insufficient soft-tissue discrimination for tumors located within anatomically complex regions such as the upper abdomen and pelvis, while repeated imaging introduces additional ionizing radiation exposure. Moreover, pre-treatment verification alone cannot fully account for target displacement that occurs during treatment as a consequence of respiration, gastrointestinal motion, or other physiological processes. Motion-encompassing approaches can compensate for some of this uncertainty but may require larger treatment volumes, whereas respiratory gating, implanted fiducial tracking, and other motion-management techniques can increase workflow complexity and, in selected applications, introduce additional procedural burdens (3,5). These limitations have stimulated development of technologies capable of direct soft-tissue visualization, continuous motion assessment, and adaptation of treatment plans to the patient's anatomy on the day of treatment.

Magnetic resonance-guided radiotherapy (MRgRT) represents one of the most important developments in this evolving landscape. Hybrid MR-linear accelerator systems combine high-contrast soft-tissue imaging with radiation delivery and can facilitate real-time visualization, gating, and online adaptive radiotherapy without the additional imaging dose associated with repeated X-ray-based verification (1,6). Clinical applications have expanded across abdominal, pelvic, thoracic, and other tumor sites, including settings in which tumors lie close to dose-limiting organs at risk (6–9). Online adaptation may permit modification of target and organ-at-risk contours and re-optimization of treatment plans in response to daily anatomical changes. However, much of the reported advantage remains based on institutional cohorts, feasibility studies, dosimetric comparisons, and relatively early clinical experience. Consequently, improvements in geometric accuracy and dose conformity should not automatically be interpreted as evidence of superior long-term survival or universal clinical benefit.

The scope of image guidance is also extending beyond anatomical localization. Functional and multiparametric imaging approaches are increasingly being investigated for characterization of intratumoral biological heterogeneity and for identification of regions with differing metabolic activity, cellularity, perfusion, or treatment resistance. Parallel developments in artificial intelligence, automated segmentation, deformable image registration, and adaptive treatment planning have the potential to reduce the time and personnel demands associated with online adaptation. At the same time, advanced image-guided platforms introduce substantial implementation challenges, including capital and maintenance costs, specialized quality-assurance requirements, prolonged treatment sessions, workforce demands, and variable institutional capacity (10,11). These considerations are particularly important when evaluating whether a technologically more sophisticated approach provides sufficient incremental clinical value over optimized conventional IGRT.

The contemporary evidence base is therefore characterized by a contrast between rapidly advancing technological capability and a less mature body of comparative clinical-outcome evidence. Although the geometric and dosimetric advantages of modern image guidance are well recognized, the magnitude of improvement in clinically meaningful outcomes varies by tumor site, treatment technique, patient selection, and study design. Direct randomized comparisons between resource-intensive adaptive platforms and optimized contemporary CBCT-based treatment remain limited, while existing reports differ considerably in dose-fractionation schedules, motion-management strategies, toxicity measures, and definitions of treatment response or local control. In addition, long-term safety, cost-effectiveness, workflow scalability, and applicability in resource-constrained healthcare systems remain incompletely characterized (10–12). These uncertainties make it increasingly difficult for clinicians and institutions to determine which technological advances represent meaningful changes in therapeutic value and which primarily provide technical or dosimetric improvements.

An updated narrative synthesis is therefore warranted to integrate the rapidly evolving technical and clinical literature while critically distinguishing established benefits from emerging or uncertain claims. Unlike a systematic review focused on a narrowly defined intervention and outcome, a narrative approach is appropriate for examining the heterogeneous technological evolution of IGRT, its diverse clinical applications, implementation requirements, and unresolved translational questions across multiple solid-tumor sites. Accordingly, this review aims to critically evaluate contemporary image-guided radiotherapy technologies, including volumetric image guidance, surface guidance, motion-management systems, MR-guided and online adaptive radiotherapy, and emerging functional and automated approaches. The review specifically asks how these technologies improve treatment precision and normal-tissue sparing, what evidence supports improvements in clinically meaningful outcomes, and which methodological, technological, economic, and implementation barriers currently limit their broader adoption in patients with solid tumors.

MATERIAL AND METHODS

This narrative review was conducted to synthesize contemporary evidence on the technological evolution, clinical applications, therapeutic implications, and implementation challenges of image-guided radiotherapy (IGRT) in patients with solid tumors. The review was designed to provide an integrative clinical and technical perspective rather than a quantitative comparison of a single intervention. The evidence base included peer-reviewed clinical studies, translational radiation-physics reports, prospective investigations, randomized trials, observational studies, and relevant review literature addressing established and emerging image-guidance technologies in radiotherapy.

Literature was considered relevant when it addressed image-guided treatment delivery in solid malignancies and contributed evidence concerning treatment localization, target-volume definition, motion management, adaptive radiotherapy, normal-tissue sparing, treatment-related toxicity, clinical outcomes, workflow feasibility, or implementation. Particular emphasis was placed on evidence concerning planar and volumetric kilovoltage imaging, cone-beam computed tomography, surface-guided radiation therapy, four-dimensional and respiratory motion-management approaches, real-time target tracking, magnetic resonance-guided radiotherapy, online adaptive radiotherapy, functional imaging, and emerging artificial intelligence-supported treatment workflows. Studies involving thoracic, abdominal, pelvic, central nervous system, and other solid-tumor sites were considered when they provided clinically or technically relevant information on the application of these modalities.

Evidence was organized according to the principal technological and clinical domains of IGRT. The synthesis first considered the transition from conventional planar verification to volumetric image guidance and its implications for correction of interactional anatomical variation. Subsequent evidence was examined in relation to intrafraction motion management, including respiratory gating, surface guidance, and real-time target tracking. Magnetic resonance-guided radiotherapy and online adaptive treatment were evaluated with particular attention to soft-tissue visualization, treatment adaptation, target-dose optimization, organ-at-risk protection, and clinical feasibility. Functional positron emission tomography and multiparametric magnetic resonance imaging were considered in the context of biologically informed target characterization and dose adaptation, while emerging artificial intelligence applications were evaluated primarily in relation to automated segmentation, image registration, adaptive planning, quality assurance, and treatment-workflow efficiency.

The evidence was synthesized narratively because of substantial heterogeneity in tumor sites, imaging platforms, radiation-delivery techniques, dose-fractionation schedules, study designs, and reported outcomes. Findings from randomized or prospective clinical investigations were interpreted separately from retrospective institutional series, feasibility studies, technical reports, and dosimetric comparisons where the distinction was relevant to the strength of inference. Greater interpretive weight was given to clinical evidence demonstrating patient-centered outcomes, including treatment-related toxicity, local tumor control, survival, and treatment feasibility, whereas geometric and dosimetric studies were used primarily to characterize technical precision, target coverage, margin reduction, and organ-at-risk sparing. Improvements in imaging accuracy or dose distribution were therefore not considered equivalent to demonstrated improvements in long-term clinical outcomes.

Critical appraisal focused on the methodological and translational limitations of the available evidence, including study design, sample size, duration of follow-up, patient selection, comparability of treatment groups, variability in treatment protocols, heterogeneity of outcome definitions, and the distinction between historical and concurrent comparisons. Particular attention was given to the extent to which reported clinical benefits could be attributed to the image-guidance modality itself rather than to differences in patient selection, tumor characteristics, radiation dose, fractionation, institutional expertise, or accompanying technological advances. The synthesis also considered practical determinants of clinical implementation, including treatment duration, quality-assurance requirements, workforce expertise, infrastructure, economic burden, scalability, and applicability across healthcare systems with differing resource availability.

The final synthesis integrated technical performance, clinical outcomes, methodological certainty, and implementation considerations to determine where advanced IGRT technologies provide established clinical or dosimetric advantages, where evidence remains preliminary, and which areas require further comparative investigation. Particular emphasis was placed on avoiding equivalence between technological sophistication and clinical superiority and on identifying priorities for prospective multicenter research, standardized outcome reporting, longer-term safety assessment, and efficient adaptive treatment workflows.

RESULTS

The earliest and most established component of IGRT is the transition from planar skeletal verification to volumetric assessment of daily anatomy. Conventional kilovoltage and megavoltage radiography remain useful for correction of gross patient-positioning errors and for treatment sites in which bony structures provide a reliable geometric surrogate.

Their principal limitation is the inability to characterize three-dimensional soft-tissue deformation or non-rigid displacement of internal targets. Cone-beam CT addressed an important component of this problem by permitting volumetric visualization immediately before treatment, thereby improving recognition of interfractional changes in patient positioning and internal anatomy (2).

The technical benefits of volumetric verification are well established, but the magnitude of downstream clinical benefit varies with tumor site, target visibility, radiation dose, treatment fractionation, and proximity of critical organs. Accordingly, improved localization accuracy should be interpreted as a prerequisite for safer treatment intensification rather than as independent proof of improved survival.

Management of intrafractional motion represents a second major evidence domain. Respiratory displacement can undermine the geometric precision achieved during pre-treatment verification, particularly for thoracic and upper-abdominal targets. Motion-encompassing strategies such as four-dimensional CT and internal target volume generation provide one solution but may increase the volume of normal tissue encompassed by treatment fields. Respiratory gating, breath-hold techniques, external surface monitoring, and direct or surrogate-based target tracking have therefore been developed to reduce uncertainty during treatment delivery (3,4,13).

SGRT is particularly attractive because it allows continuous, non-ionizing monitoring of the patient's external surface and has become an important component of positioning and respiratory-control workflows. Nevertheless, the relationship between external surface displacement and internal tumor motion is not uniform across anatomical sites, and the clinical value of any motion-management strategy depends on appropriate patient selection and validation of the chosen surrogate.

Table 1. Summary of Representative Evidence Supporting Contemporary Image-Guided Radiotherapy

Evidence domain	Representative source	Study design/type	Sample	Principal contribution to synthesis	Evidence interpretation
General MR-guided radiotherapy	Chin et al. (1)	Review	NR	Summarized technical development, clinical implementation, soft-tissue visualization, and adaptive potential of MR-guided radiotherapy	Broad supporting evidence; largely dependent on heterogeneous primary studies
General clinical applications of MRgRT	Ladbury et al. (6)	Narrative review	NR	Synthesized contemporary clinical applications of MR-guided radiotherapy across tumor sites	Useful for clinical context; does not constitute direct comparative evidence
Conventional IGRT	De Crevoisier et al. (2)	Review	NR	Described contemporary image-guidance approaches and their role in reducing geometric uncertainty during radiotherapy	Supports established role of IGRT in treatment verification
Motion management	Jegal et al. (3)	Review	NR	Evaluated advanced motion-management and image-guidance technologies in photon radiotherapy	Supports technical rationale for management of respiratory and intrafractional motion
Surface-guided radiotherapy	Al-Hallaq et al. (4)	Review/expert synthesis	NR	Examined the role of SGRT in patient positioning, monitoring, and treatment safety	Strong technical and safety rationale; clinical outcome evidence remains indication-specific
Breast motion management	Piruzan et al. (13)	Review	NR	Synthesized motion-management techniques relevant to breast radiotherapy	Supports respiratory-control strategies, particularly where cardiac exposure is clinically relevant
Hepatic metastases	Hoegen et al. (14)	Randomized phase II trial	NR	Compared MR-guided adaptive SBRT with an ITV-based stereotactic approach for hepatic metastases	Higher-level comparative evidence within a specific indication
Gynecological malignancies	Portelance et al. (15)	Clinical review/experience	NR	Examined online MR-guided radiotherapy for gynecological cancers	Supports feasibility of adaptive workflows; evidence remains site-specific
Liver tumors	Padgett et al. (16)	Clinical/technical assessment	NR	Evaluated online adaptive MR-guided SBRT for liver cancers	Supports adaptive planning and organ-at-risk management in abdominal treatment
Renal cell carcinoma	Keller et al. (17)	Review	NR	Evaluated adaptive MR-guided SBRT as an emerging approach for renal cell carcinoma	Promising application with comparatively limited mature outcome evidence
Abdominal and pelvic tumors	Yoon et al. (8)	Clinical outcomes study	NR	Reported clinical experience with stereotactic MR-guided adaptive radiotherapy for primary and metastatic abdominal and pelvic tumors	Provides patient-level clinical outcome evidence but is not equivalent to randomized comparison
Adrenal metastases	Hoegen et al. (18)	Clinical study	NR	Evaluated stereotactic MR-guided online adaptive treatment with emphasis on ablative dosing and organ-at-risk sparing	Supports feasibility and dosimetric optimization in a selected population
NSCLC	Crockett et al. (9)	Initial clinical experience	NR	Reported early clinical implementation of MR-guided radiotherapy for non-small cell lung cancer	Early feasibility evidence; limited for definitive comparative-effectiveness conclusions
Prostate cancer	Benitez et al. (22)	Review	NR	Examined MR-guided radiotherapy in the context of prostate ultrahypofractionation	Supports technological rationale and emerging clinical application
Brain tumors	Guerini et al. (21)	Systematic review	NR	Synthesized clinical and technical experience with hybrid MRI-linac systems in brain tumors	Structured evidence synthesis but dependent on quality of included primary studies
Ultra-central lung tumors	Salvestrini et al. (20)	Review	NR	Examined contemporary SBRT challenges and treatment considerations in ultra-central lung disease	Highlights the importance of precision and organ-at-risk constraints
Healthcare implementation	Courtney et al. (10)	Health-policy/economic review	NR	Examined economic, policy, and care-delivery implications of MRI-guided radiotherapy	Supports implementation and value-based assessment rather than treatment-effect estimation
Future MR-guided radiotherapy	Goodburn et al. (11)	Technical review	NR	Identified technological opportunities and implementation challenges for MRI in radiotherapy	Supports future-development and infrastructure considerations
Radiation oncology development	Corradini et al. (12)	Expert review/symposium synthesis	NR	Integrated technological and biological developments across modern radiation oncology	Broad contextual evidence rather than direct comparative effectiveness evidence

NR: not reported in the supplied manuscript; IGRT: image-guided radiotherapy; MRgRT: magnetic resonance-guided radiotherapy; SGRT: surface-guided radiation therapy; SBRT: stereotactic body radiation therapy; ITV: internal target volume; NSCLC: non-small cell lung cancer.

Table 2. Comparative Characteristics and Evidence Profile of Major Image-Guided Radiotherapy Modalities

Modality	Principal imaging advantage	Intrafractional capability	Additional ionizing imaging exposure	Principal clinical role	Main limitations	Overall evidence profile
Planar kV/MV imaging	High spatial resolution for bony anatomy	Limited	Low	Skeletal alignment and selected marker-based verification	Poor soft-tissue visualization; limited assessment of non-rigid anatomical change	Mature technical role but limited for direct soft-tissue targeting
Cone-beam CT	Three-dimensional volumetric anatomical verification	Primarily pre- or post-treatment	Present	Broad application across pelvic, thoracic, and head-and-neck radiotherapy	Scatter artifacts, reduced soft-tissue contrast, limited real-time motion assessment	Established geometric benefit; clinical effect depends on tumor site and treatment context
SGRT	High-resolution external surface monitoring	Continuous	None	Positioning, motion monitoring, breath-hold treatment, selected cranial applications	External surface may not always represent internal target position	Strong technical and safety evidence; outcome evidence is indication-dependent
Respiratory gating / real-time tracking	Temporal control of moving targets	Continuous or phase-dependent	Technique-dependent	Thoracic and upper-abdominal targets affected by respiration	Workflow complexity, prolonged treatment, surrogate-target uncertainty, and potential need for fiducial implantation	Strong technical rationale; comparative patient-outcome evidence remains heterogeneous

Modality	Principal imaging advantage	Intrafractional capability	Additional ionizing imaging exposure	Principal clinical role	Main limitations	Overall evidence profile
MR-guided radiotherapy	Superior soft-tissue contrast	Continuous or near-continuous	None from MRI	Abdominal, pelvic, prostate, and other soft-tissue targets	High infrastructure cost, workflow complexity, longer treatment sessions	Strong imaging and dosimetric evidence with expanding but still heterogeneous clinical evidence
Online adaptive MRgRT	Daily anatomical reassessment with plan adaptation	Integrated with real-time guidance	None from MRI	Targets adjacent to mobile or dose-limiting organs at risk	Time, staffing, contouring, optimization, and QA burden	Promising clinical evidence; relatively limited randomized comparative evidence
Functional PET/mpMRI guidance	Characterization of biological heterogeneity	Not routinely continuous	Modality-dependent	Biological target definition and investigational dose painting	Uncertain biological stability, standardization, validation, and clinical benefit	Predominantly emerging or investigational evidence
AI-supported adaptive workflows	Automation of segmentation, registration, planning, and QA	Potentially real-time	None inherent to AI	Reduction of adaptive-workflow burden	Generalizability, validation, QA, regulatory, and implementation concerns	Rapidly evolving; clinical-effect evidence less mature than technical-development evidence

kV: kilovoltage; MV: megavoltage; CT: computed tomography; SGRT: surface-guiduided radiation therapy; MRgRT: magnetic resonance-guided radiotherapy; PET: positron emission tomography; mpMRI: multiparametric magnetic resonance imaging; AI: artificial intelligence; QA: quality assurance.

The strongest technological transition beyond conventional volumetric IGRT has occurred with MR-guided radiotherapy. Hybrid MR-linear accelerator platforms offer superior soft-tissue contrast compared with conventional X-ray-based verification and enable repeated or continuous visualization without additional ionizing imaging exposure (1,6). Their principal clinical advantage is most apparent in anatomically complex regions where tumor and adjacent normal tissues may be poorly distinguished on CBCT. Clinical experience has expanded across abdominal, pelvic, thoracic, renal, prostate, gynecological, and metastatic disease settings (8,9,15–18,22). Across these studies, the most consistent evidence concerns improved target visualization, adaptive planning feasibility, maintenance of organ-at-risk constraints, and the ability to reconsider the treatment plan in response to daily anatomical change.

Online adaptive radiotherapy extends image guidance from localization to active modification of the treatment plan. This approach is particularly relevant when the spatial relationship between the tumor and nearby gastrointestinal or other radiosensitive organs changes substantially between treatment fractions. Evidence from liver, adrenal, abdominal, pelvic, and other treatment settings demonstrates the technical feasibility of re-contouring and treatment-plan adaptation using daily anatomy (8,16,18). A randomized phase II comparison in hepatic metastases provides a comparatively stronger level of evidence within this otherwise largely heterogeneous literature (14). However, the overall evidence base should not be interpreted as uniformly randomized or comparative. Many reports remain institutional clinical series, early prospective experiences, technical evaluations, or narrative syntheses, limiting the certainty with which improvements in dosimetry can be translated into improvements in survival or other long-term patient-centered outcomes.

The distinction between dosimetric benefit and clinical superiority is particularly important when interpreting reported experiences with ablative stereotactic treatment. The supplied literature supports the feasibility of delivering highly conformal treatment in anatomically challenging sites, but the evidence is heterogeneous with respect to tumor stage, treatment intent, radiation dose, fractionation, systemic therapy, and comparator selection. Historical comparisons may suggest favorable local control or survival in selected cohorts, but they are vulnerable to differences in patient selection, tumor burden, performance status, institutional expertise, and accompanying improvements in oncological care. For this reason, the present synthesis assigns greater certainty to conclusions regarding visualization, geometric accuracy, adaptive feasibility, and organ-at-risk sparing than to claims of universal survival benefit.

The evidence base for surface guidance and motion management is similarly strongest for technical precision and treatment safety. Reviews addressing SGRT and respiratory-motion management support their use for selected indications in which reproducible positioning or respiratory control is clinically important (3,4,13). Their value is especially apparent when steep dose gradients or critical-organ proximity make relatively small geometric errors consequential. However, motion-management techniques are not interchangeable. External surface monitoring, respiratory gating, internal fiducial tracking, and motion-encompassing target definition differ in invasiveness, workflow complexity, dependence on surrogate accuracy, treatment efficiency, and applicability across anatomical sites.

Functional and biological image guidance represents a less mature extension of the IGRT paradigm. PET and multiparametric MRI can characterize biological features that are not apparent from anatomical imaging alone, including metabolic activity, diffusion-related cellularity, perfusion, and potentially treatment-resistant subregions. These techniques provide a rationale for biologically informed target definition and dose-painting strategies, but the clinical significance of spatially heterogeneous imaging biomarkers remains less firmly established than the geometric benefits of conventional image guidance. The stability of biological targets over time, optimal imaging thresholds, reproducibility across platforms, and evidence that biological dose escalation improves clinically meaningful outcomes without unacceptable toxicity remain important areas for investigation (12).

Technological sophistication also introduces important implementation trade-offs. MR-guided and online adaptive treatments require specialized infrastructure, multidisciplinary expertise, image interpretation, contour adaptation, plan optimization, and treatment-specific quality assurance. These requirements can increase treatment-session duration and reduce patient throughput relative to conventional image-guided workflows. Economic and health-policy analyses therefore emphasize that the value of advanced IGRT should be assessed according to the clinical problem being addressed rather than the sophistication of the platform itself (10,11). Patients with mobile tumors located immediately adjacent to dose-limiting organs may derive substantially greater practical benefit from online adaptation than patients receiving conventional treatment for anatomically stable targets with a wide therapeutic margin.

Across the evidence base, important methodological limitations were recurrent. The literature includes randomized studies in selected indications, but a substantial proportion of the evidence derives from retrospective cohorts, prospective feasibility studies, institutional experiences, technical analyses, and dosimetric investigations. Follow-up is frequently insufficient to define long-term toxicity or late treatment-related complications, while patient selection and institutional expertise may limit external validity. Outcome definitions also vary across studies, particularly for toxicity, local control, geometric accuracy, and treatment feasibility. These differences reduce direct comparability and preclude interpretation of the current literature as a homogeneous body of treatment-effect evidence.

Overall, the synthesis indicates that the most robust and consistent benefits of contemporary IGRT relate to improved anatomical verification, more precise target localization, enhanced management of treatment-related motion, and better adaptation to day-to-day anatomical variation. Evidence supporting reductions in normal-tissue exposure and improved treatment feasibility is also substantial in selected clinical contexts. In contrast, definitive evidence that increasingly sophisticated image-guidance platforms independently improve overall survival, long-term disease control, or cost-effectiveness across broad solid-tumor populations remains comparatively limited. The current evidence therefore supports a risk-adapted approach in which advanced image guidance and online adaptation are preferentially applied when tumor motion, soft-tissue visibility, proximity to critical structures, or narrow therapeutic margins create a clinically meaningful need for greater treatment precision.

DISCUSSION

This narrative review evaluated how contemporary image-guided radiotherapy technologies influence treatment precision, normal-tissue sparing, motion management, adaptive treatment, and clinically meaningful outcomes across solid malignancies. The synthesis indicates that the most established benefits of IGRT lie in improved anatomical verification, reduction of geometric uncertainty, more reliable management of interfractional and intrafractional motion, and improved conformity between the planned and delivered radiation dose. The evidence is particularly persuasive for the technical and dosimetric advantages of volumetric image guidance, surface monitoring, and magnetic resonance-guided adaptive treatment. In contrast, evidence that increasingly sophisticated guidance platforms independently improve long-term survival, disease control, or cost-effectiveness across broad solid-tumor populations remains less mature. This distinction is central to interpretation of the literature because technological precision, although clinically important, should not itself be considered a surrogate for improved oncological outcome.

The present synthesis is consistent with earlier reviews describing the transition from planar verification toward volumetric and adaptive image guidance as a major development in radiation delivery (1,2,6). Conventional CBCT has substantially strengthened daily anatomical verification by permitting direct assessment of three-dimensional

patient anatomy, but its limitations in soft-tissue contrast and real-time intrafractional visualization remain clinically relevant, particularly for abdominal and pelvic targets. Contemporary verification and delivery frameworks increasingly integrate imaging with treatment adaptation rather than treating image guidance solely as a pre-treatment positioning procedure (22). The current review extends this perspective by emphasizing that the clinical value of increasingly complex imaging should be evaluated according to the specific uncertainty it resolves. Routine adoption of a more technologically intensive platform is not necessarily justified when conventional volumetric guidance already provides sufficient geometric confidence for a stable target.

Motion management represents another domain in which the evidence supports a clear technical rationale but a more context-dependent clinical benefit. Respiratory gating, breath-hold methods, SGRT, four-dimensional imaging, and target-tracking approaches can reduce uncertainty arising from respiratory or other physiological movement (3,4,13). These strategies are particularly important when steep dose gradients are used or when mobile targets lie close to dose-limiting structures. However, the optimal method depends on tumor site, target visibility, the reliability of external or internal surrogates, treatment duration, and patient tolerance. Recent work on respiratory-motion prediction further illustrates the movement toward computational approaches capable of anticipating cyclic target displacement rather than simply detecting it after it occurs (23). Such developments are promising, but their contribution to patient outcomes requires validation beyond technical accuracy endpoints.

MR-guided radiotherapy represents the clearest transition from anatomical verification to active online adaptation. The superior soft-tissue visualization provided by hybrid MR-linear accelerator systems is particularly relevant in the abdomen and pelvis, where day-to-day variation in bowel, stomach, bladder, and other mobile structures can substantially alter the relationship between target and organs at risk (1,6–8). Clinical experience in liver, adrenal, renal, gynecological, prostate, thoracic, and other tumor sites demonstrates that daily reassessment and plan adaptation are feasible and can improve target coverage while maintaining organ-at-risk constraints (8,9,14–20). Importantly, however, the level of evidence is not uniform. Although randomized phase II evidence is available in selected settings such as hepatic metastases (14), much of the wider literature consists of institutional cohorts, early clinical experiences, technical studies, and disease-specific reviews. The appropriate interpretation is therefore that the technical and dosimetric benefits of MR-guided adaptation are increasingly established, whereas the magnitude of incremental long-term clinical benefit remains indication-specific.

The increasing use of hypofractionated and stereotactic regimens makes this distinction particularly important. High-dose-per-fraction treatment increases the clinical consequence of geometric error because a relatively small displacement can expose critical structures or compromise target coverage during a fraction. Modern planning for hypofractionated radiotherapy and SRS/SBRT therefore relies heavily on accurate image guidance, immobilization, motion characterization, and organ-at-risk assessment (24). Advanced IGRT is consequently most compelling when it enables a treatment strategy that could not otherwise be delivered safely, such as adaptive treatment of a mobile abdominal target immediately adjacent to a radiosensitive organ. By contrast, the incremental value may be smaller in anatomically stable situations in which conventional image guidance already provides sufficient localization accuracy.

The findings also support a cautious interpretation of reported improvements in clinical outcomes. Several institutional series describe favorable tumor control, toxicity profiles, or survival after adaptive and stereotactic treatment, but such observations are susceptible to patient selection, differences in tumor burden, performance status, systemic therapy, institutional expertise, radiation dose, and fractionation. Comparisons with historical cohorts are particularly vulnerable to confounding because improvements in imaging, systemic therapy, supportive care, treatment planning, and patient selection often occur simultaneously. Accordingly, apparent survival gains cannot be attributed exclusively to the image-guidance platform unless supported by appropriately controlled comparative evidence. The established evidence is strongest for improved visualization, geometric accuracy, adaptive feasibility, and normal-tissue dosimetry; attribution of survival improvement requires a higher evidentiary threshold.

Functional PET and multiparametric MRI introduce a further conceptual shift from anatomical precision toward biologically individualized radiation treatment. These techniques can identify spatial variations in metabolism, diffusion, perfusion, and potentially radioresistant tumor subregions, creating a rationale for biologically directed dose painting. This direction is consistent with the broader evolution of radiation oncology from purely anatomical

targeting toward integration of imaging biomarkers and tumor biology (12). Nevertheless, biological imaging raises additional uncertainties concerning temporal stability of imaging-defined subvolumes, reproducibility across platforms, threshold selection, and whether escalation to imaging-defined regions improves meaningful clinical outcomes. At present, biologically guided adaptation should therefore be regarded as an emerging strategy rather than an established replacement for anatomically guided treatment.

Artificial intelligence may ultimately determine whether increasingly sophisticated adaptive workflows can be implemented at scale. Automated contouring, deformable image registration, plan optimization, motion prediction, and treatment-quality assurance could reduce the human-resource burden associated with daily adaptation and shorten treatment sessions. The potential benefit is not merely greater speed; automation may also improve standardization between institutions and reduce dependence on highly specialized teams. However, implementation requires rigorous external validation, prospective quality assurance, assessment of failure modes, and clinically meaningful performance benchmarks. Automated workflows should therefore be evaluated on the basis of safety, reproducibility, workflow efficiency, and patient outcomes rather than algorithmic performance alone.

The economic and organizational implications are equally important. MR-guided adaptive radiotherapy requires substantial capital investment, specialized infrastructure, trained multidisciplinary staff, treatment-unit time, and ongoing quality assurance (10,11). These requirements create an opportunity-cost problem for health systems, particularly in resource-constrained environments where the same investment could potentially expand access to conventional radiotherapy for a larger number of patients. The evidence therefore supports a risk-stratified rather than technology-driven implementation model. Advanced adaptive platforms are most defensible when conventional guidance cannot adequately manage target motion, soft-tissue uncertainty, or organ-at-risk proximity. In lower-complexity indications, optimized CBCT-based treatment may remain clinically appropriate and operationally more efficient.

This review has several limitations that arise specifically from its narrative design and evidence base. Literature selection was not conducted through a prospectively registered systematic-review protocol, and no formal dual-reviewer screening process or standardized risk-of-bias instrument was applied. The synthesis may therefore be susceptible to selection bias and cannot provide the completeness guarantees expected from a systematic review. In addition, the included evidence is methodologically heterogeneous and ranges from randomized investigations to retrospective series, technical studies, narrative reviews, systematic reviews, and expert syntheses. Quantitative pooling was consequently inappropriate. Several clinically important outcomes are also reported inconsistently across the underlying literature, including toxicity, local control, geometric accuracy, adaptive-plan benefit, treatment duration, and patient-reported outcomes. These limitations restrict direct comparison across technologies and mean that the strength of conclusions differs considerably by outcome and clinical setting.

A further limitation concerns the maturity and external validity of the underlying clinical evidence. Advanced image-guided platforms are often introduced at highly specialized tertiary centers with experienced radiation oncologists, physicists, dosimetrists, and dedicated adaptive-treatment workflows. Outcomes from these environments may not be reproducible in lower-volume centers or health systems with limited technical support. In addition, short follow-up in many early clinical series is better suited to assessing feasibility and acute toxicity than late organ injury, second malignancy risk, or durable survival. The current synthesis therefore supports technical superiority in selected contexts more strongly than universal clinical superiority.

From a clinical perspective, patient selection should be driven by the magnitude and type of treatment uncertainty. Tumor motion, poor soft-tissue visibility, close proximity to critical organs, substantial day-to-day anatomical variation, and the use of highly ablative fractionation are reasonable factors for prioritizing advanced image guidance or online adaptation. At the policy level, implementation should be accompanied by explicit indication criteria, modality-specific quality-assurance standards, workforce planning, and health-economic evaluation. Technology assessment should compare advanced platforms not only with historical radiotherapy but with optimized contemporary alternatives, because the relevant policy question is whether incremental benefit justifies incremental cost and complexity.

Future research should prioritize adequately powered multicenter randomized or pragmatic comparative trials in clinical settings where genuine uncertainty exists between online adaptive treatment and optimized conventional

IGRT. Trials should use standardized definitions of local control, toxicity, adaptive-plan benefit, treatment time, patient-reported outcomes, and resource utilization; incorporate longitudinal follow-up sufficient to detect late adverse effects; and stratify patients according to tumor motion, anatomical complexity, and proximity to organs at risk. Prospective economic evaluations should be embedded within clinical trials rather than performed solely from modeled assumptions. AI-enabled adaptive workflows require external multicenter validation and prospective assessment of segmentation error, registration failure, plan-quality variation, and human-override frequency. Finally, research on functional image-guided dose painting should establish reproducible biological targets and demonstrate that biomarker-guided escalation improves patient-centered outcomes before routine clinical adoption.

CONCLUSION

Contemporary image-guided radiotherapy has substantially strengthened the precision of radiation delivery by improving target localization, motion management, soft-tissue visualization, and adaptation to day-to-day anatomical change. The most robust evidence supports geometric and dosimetric benefits, with clinically meaningful reductions in treatment uncertainty and improved organ-at-risk protection in selected high-complexity settings, whereas evidence for universal improvements in long-term survival, disease control, or cost-effectiveness remains less definitive. Advanced modalities such as MR-guided online adaptive radiotherapy should therefore be implemented according to clinical need rather than technological availability, with priority given to mobile or poorly visualized tumors situated close to critical normal structures. Future progress depends on multicenter comparative trials, standardized clinical endpoints, mature follow-up, prospective economic evaluation, and validated automation capable of translating technical precision into reproducible and equitable patient benefit.

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