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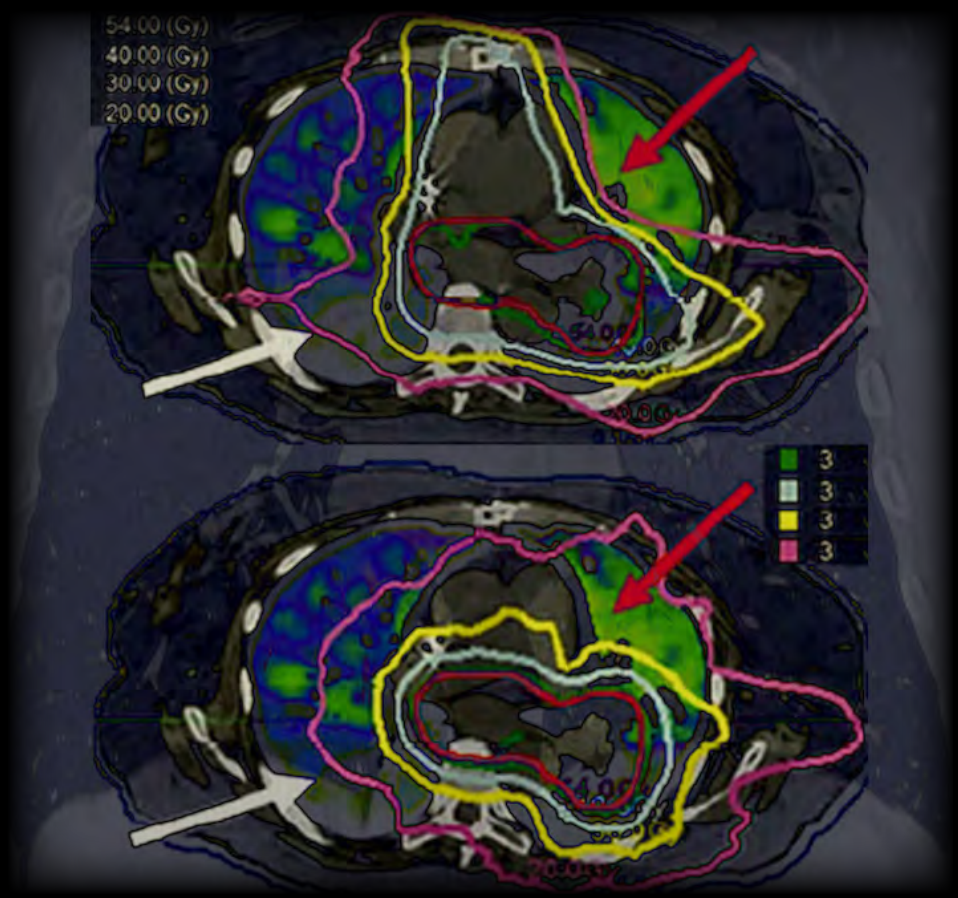

Review
4DCT Ventilation Functional Avoidance in Lung Cancer Radiation Therapy: Clinical Evidence, Workflow, and Quality Assurance

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Respiratory Motion Management in Lung Cancer Radiation Therapy: A Practical Framework for Technique Selection and Treatment Delivery

Research
Practice Changes and Geographic Reach of Postprostatectomy Radiation Therapy After NRG-GU003

Radiation Oncology Case
Stage 1A NLPHL Complete Response to 4 Gy VLDRT

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On the cover: Image adapted from Figure 2 of "4DCT Ventilation Functional Avoidance in Lung Cancer Radiation Therapy: Clinical Evidence, Workflow, and Quality Assurance" by Nader Ghassemi, PHD. Cover design by *Applied Radiation Oncology*.

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Matching Innovation to Clinical Need

John J. Suh, MD, FASTRO, FACR

Dr Suh is the editor-in-chief of *Applied Radiation Oncology*, and Professor and Enterprise Chair of the Department of Radiation Oncology at the Taussig Cancer Institute, Rose Ella Burkhardt Brain Tumor and Neuro-Oncology Center, Cleveland Clinic, Cleveland, OH.

Advances in imaging and treatment delivery have given radiation oncology increasingly sophisticated tools to account for respiratory motion and limit dose to healthy tissue. The challenge is not simply whether these technologies are available, but when their added complexity provides a meaningful clinical advantage.

The review articles in this issue of *Applied Radiation Oncology* address that question from complementary perspectives. "Respiratory Motion Management in Lung Cancer Radiation Therapy: A Practical Review and Decision Framework for Technique Selection and Treatment Delivery" examines approaches to respiratory motion management, including breath hold, respiratory gating, abdominal compression, and surface-guided monitoring, emphasizing selection of the least complex strategy that maintains target coverage and can be reproduced and verified throughout treatment.

"4DCT Ventilation Functional Avoidance in Lung Cancer Radiation Therapy: Clinical Evidence, Workflow, and Quality Assurance" shifts the focus from how the lung moves to the functionality of its different regions. Four-dimensional CT ventilation imaging may help identify better-functioning lung for preferential sparing, but current evidence supports selective rather than routine use.

The importance of translating evidence into practice is also reflected in this issue's research article, "Practice Changes and Geographic Reach of Post-Prostatectomy Radiation Therapy After NRG-GU003." At a multisite institution, the use of moderately hypofractionated regimens increased substantially after the trial was published, along with patient volume. The findings illustrate how clinical trial results can alter practice relatively quickly, while also raising important questions about whether greater treatment efficiency translates into broader access to care.

Our radiation oncology case, "Stage 1A NLPHL Complete Response to 4 Gy VLDRT," also explores whether more conservative treatment can achieve the desired outcome. A young adult with stage 1A nodular lymphocyte-predominant Hodgkin lymphoma received 4 Gy in 2 fractions rather than the initially recommended 30 Gy, with no acute toxicity and complete metabolic response at 3 months. The case highlights the potential of carefully selected dose de-escalation to reduce treatment burden and long-term toxicity.

Technology is also viewed through an educational lens in this issue's Resident Voice editorial, "Augmented Reality Can Improve Real-World Brachytherapy." The authors explore how augmented reality may enhance brachytherapy training by allowing residents to visualize anatomy, applicator placement, and procedural steps in a more immersive and interactive environment. Their perspective highlights the potential for these tools to supplement hands-on experience and mentorship, while helping trainees build procedural understanding and confidence before entering the treatment suite.

The future of radiation oncology will undoubtedly bring more powerful and precise technologies, more detailed imaging, and increasingly personalized treatment. Our responsibility is to ensure that innovation remains grounded in evidence, pragmatism, and the needs of the patients we serve.

Thank you for your continued support of *Applied Radiation Oncology*.

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4DCT Ventilation Functional Avoidance in Lung Cancer Radiation Therapy: Clinical Evidence, Workflow, and Quality Assurance

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Abstract

Radiation pneumonitis and post-treatment pulmonary function decline remain clinically important toxicities after curative-intent thoracic radiation therapy. Conventional whole-lung dose constraints such as mean lung dose and V_{20} remain fundamental because they are practical, validated, and embedded in standard thoracic planning, but they implicitly treat lung parenchyma as functionally uniform. In many patients with lung cancer, comorbidities such as emphysema, airway obstruction, atelectasis, prior infection, and tumor-related dysfunction produce marked regional heterogeneity in baseline pulmonary function. Functional avoidance attempts to preferentially spare better-functioning lung while preserving target coverage and established organ-at-risk constraints. Four-dimensional CT (4DCT) adds respiratory-phase information to conventional treatment-planning CT, allowing tumor and lung motion to be incorporated into thoracic radiation therapy planning. This review focuses on 4DCT ventilation-based functional avoidance because it uses the planning 4DCT acquired for motion assessment, integrating naturally into modern thoracic simulation workflows. This convenience should not be overstated. 4DCT ventilation is a deformable-registration-derived surrogate rather than a direct physiologic measurement, and its clinical value depends on respiratory image quality, registration quality assurance, and disciplined plan review. Current prospective clinical evidence supports 4DCT ventilation functional avoidance as a promising and implementable strategy in experienced thoracic programs, particularly for conventionally fractionated curative-intent treatment of locally advanced or stage 3 non-small cell lung cancer. However, available data do not yet support its routine use in all thoracic radiation therapy patients or establish the technique as a universal standard of care.

Keywords: 4DCT ventilation imaging, functional lung avoidance, locally advanced NSCLC, stage 3 NSCLC, deformable image registration, thoracic radiation therapy, quality assurance, radiation pneumonitis

Introduction

Avoidance of radiation-induced lung toxicity is a central planning concern in thoracic radiation therapy. Mean lung dose and V_{20} (the percentage of normal lung tissue receiving 20 Gy or more) are indispensable in that regard because they are easy to interpret, are widely used in protocol design, and have a durable relationship with the risk of symptomatic pneumonitis.[1] Their limitation is conceptual rather than procedural: conventional dose-volume metrics do not distinguish between poorly functioning and well-functioning lung. In a population in which baseline lung function is often regionally abnormal,

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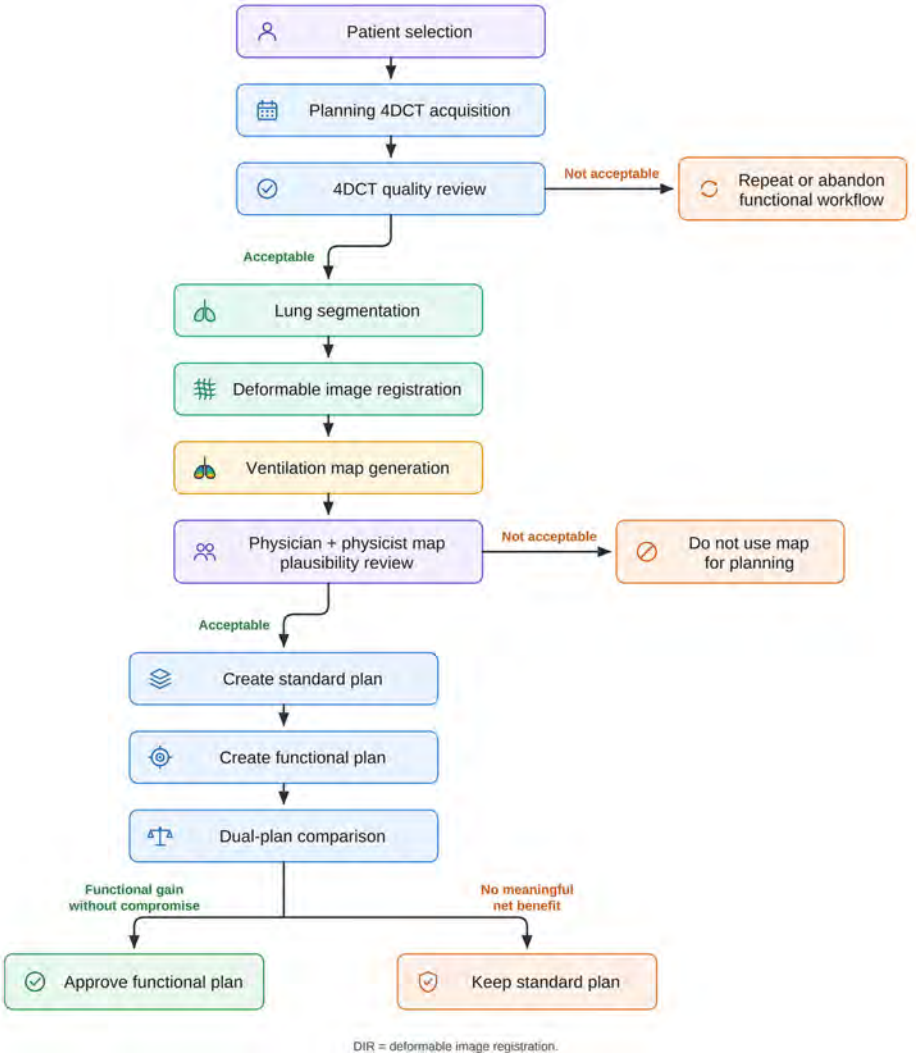
Figure 1. Clinical decision algorithm and end-to-end workflow for four-dimensional CT (4DCT) ventilation functional avoidance. Suggested clinical workflow for 4DCT ventilation-based functional avoidance, beginning with patient selection and planning 4DCT acquisition, followed by image-quality review, lung segmentation, deformable image registration (DIR), ventilation-map generation, physician-physicist map plausibility review, standard plan generation, functional plan generation, dual-plan comparison, and final plan approval. Functional planning should be layered onto standard thoracic planning rather than substituted for it; the functional plan should be selected only when it improves functional lung sparing without compromising target coverage or conventional organ-at-risk (OAR) constraints. The central decision points are whether the patient has actionable functional heterogeneity, whether the 4DCT and DIR pass quality assurance review, whether the functional plan produces meaningful functional lung sparing, and whether standard target and OAR planning requirements remain acceptable.



that simplification may obscure clinically meaningful differences in what tissue is actually being irradiated.[2-4]

Functional lung avoidance emerged from this observation. Its goal is not to replace standard thoracic constraints, but to refine them by preferentially avoiding better-functioning lung when a safe and practical opportunity to do so is available.[2,5,6] Several functional imaging platforms can support that concept, including SPECT, hyperpolarized-gas MRI, and V/Q PET/CT.[3,7-9] This review focuses on four-dimensional CT (4DCT)-derived ventilation imaging because, among currently available functional avoidance approaches, it is one of the most practical to integrate into routine thoracic radiation therapy workflows when high-quality planning 4DCT datasets are already acquired.[4,10-12] The key question is not whether the concept is attractive in principle, but whether the current evidence justifies selective clinical use and what conditions must be met before implementation should be attempted. The proposed clinical workflow is summarized in **Figure 1** and discussed in detail in the implementation and quality assurance (QA) sections.

Rationale for Functional Lung Avoidance

The rationale for functional avoidance is strongest in the same patients in whom conventional thoracic radiation therapy is most challenging: those with bulky or centrally located tumors,

nodal disease, prior smoking-related lung injury, and baseline heterogeneity in regional pulmonary function. In such patients, a conventional plan may meet standard anatomic lung constraints while still depositing substantial dose in the best-preserved lung regions.[1,2,5,6] Functional planning asks whether that distribution can be improved without compromising planning target volume (PTV) coverage or other organ-at-risk (OAR) goals.

That rationale is clinically sensible, but it is not universally actionable. Functional avoidance requires 2 conditions: First, the patient must have meaningful baseline functional heterogeneity; if the map is essentially homogeneous, there is very little information to exploit.[2,4,6] Second, the geometry must permit redistribution; if the PTV is already encasing the best-functioning lung or if sparing that region worsens esophageal, heart, cord, or target metrics, the functional plan may add complexity without real gain.[2,5,6] These findings support patient selection as a central requirement, rather than a secondary consideration. Accordingly, **Figure 1** should be read as a clinical decision algorithm rather than only a software workflow: functional avoidance is most actionable when baseline functional heterogeneity is present, the geometry permits dose redistribution, source 4DCT and deformable image registration (DIR) quality are acceptable, and the functional plan improves functional lung sparing without compromising PTV coverage or conventional OAR constraints.[2,4,6,13]

The literature now supports a fairly specific clinical use case. The clearest prospective signal has emerged in conventionally fractionated curative-intent therapy, most commonly for locally advanced or stage 3 non-small cell lung cancer (NSCLC) treated with concurrent chemotherapy.[2,6,13-16] By contrast, current data do not justify routine use for all early stage lung cancer stereotactic body radiation therapy (SBRT) cases, where treated lung volumes are smaller and the opportunity for meaningful dose redistribution may be limited.[3,4,13] Severe baseline pulmonary impairment is not, by itself, a contraindication, but it increases the importance of rigorous map review because poor image quality, irregular breathing, and anatomic distortion can all degrade the reliability of a 4DCT-derived functional surrogate.[4,12,17-19]

Generation of 4DCT Ventilation Maps

Operationally, most 4DCT ventilation workflows include respiratory-phase selection, lung segmentation, DIR between selected respiratory phases or to a reference phase, voxelwise calculation of regional expansion and/or density change, and conversion of the resulting ventilation surrogate into either a reviewed functional region or a graded planning objective. This stepwise structure is clinically important, as uncertainty can enter at each stage: source 4DCT quality, phase selection, lung contouring, DIR accuracy, ventilation algorithm choice, and final map thresholding or weighting all influence the map that is eventually used for planning.[4,10,11,17,19] A planning 4DCT acquired for motion management contains phase-resolved information about the lung across the respiratory cycle. If inhale and exhale phases can be accurately registered, voxel-wise or region-wise changes in volume and density can be used to estimate regional ventilation.[10,11] Early methods relied primarily on density change or Jacobian-based formulations.[10,11] At a practical level, commonly reported CT ventilation approaches can be grouped as density change, Jacobian or volume change, and mass conservation methods; these workflows share the same dependence on 4DCT image quality and DIR but differ in how respiratory-related anatomic change is converted into a ventilation surrogate.[10,11,17,18] More recent work has emphasized more numerically robust mass conservation approaches intended to reduce instability and improve reproducibility.[18]

For day-to-day clinical use, however, the "mathematics" matter less than the implementation implications. 4DCT ventilation is not a direct ventilation measurement. It is an image-derived biomarker that depends on segmentation, phase selection, deformable registration, and the algorithm used to convert deformation and density information into a ventilation surrogate.[4,11,12,17,18] Different software applications and processing methods can therefore produce different ventilation maps from the same source 4DCT. The practical consequence is that a center should commission one workflow, understand its failure modes, and avoid assuming that maps generated by different vendors or algorithms are interchangeable.[4,17,19]

This dependence on input data quality supports a concise presentation of technical details while clearly defining the prerequisites for reliable implementation. A clinically credible 4DCT ventilation program begins with a clinically credible 4DCT. If the planning scan shows irregular breathing, incorrect respiratory-phase sorting, major image artifacts, or incomplete visualization of tumor or lung motion, the derived functional map becomes difficult to defend regardless of the sophistication of the downstream algorithm.[4,12,19]

Validation of 4DCT Ventilation Imaging

Validation studies have established biologic plausibility but have also clarified the method's limits. Vinogradskiy et al compared 4DCT ventilation with nuclear medicine V/Q imaging and found clinically meaningful correlation, supporting the idea that CT-derived ventilation maps capture relevant regional physiology.[20] Yamamoto et al compared 4DCT-derived ventilation with pulmonary function tests and SPECT ventilation imaging, again supporting biologic relevance but not perfect equivalence.[21] Brennan et al extended this

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validation against pulmonary function test data, showing associations between 4DCT ventilation metrics and global pulmonary function across a patient cohort; however, they did not establish 4DCT ventilation as a definitive patient-specific or voxel-level physiologic truth standard.[22]

The field matured further when validation moved beyond single-institution comparisons. The Ventilation And Medical Pulmonary Image Registration Evaluation challenge was important because it demonstrated, in a multi-institutional setting, that CT ventilation results are meaningfully influenced by algorithmic choice and implementation details.[17] That message remains essential. Validation does not mean interchangeability. A method can be biologically plausible and clinically useful while still being sensitive to registration error, segmentation choices, noise, or the specific transformation model used.[4,17,18]

Accordingly, the available evidence supports a cautious interpretation of the validation literature: 4DCT ventilation has enough biologic and technical validity to justify prospective clinical testing and selective implementation, but it should still be treated as a surrogate functional biomarker rather than a definitive physiologic measurement.[4,17,18,20-23]

Functional Avoidance Planning and Dose-Function Metrics

The practical planning question is how to incorporate a functional map without destabilizing an otherwise sound thoracic workflow. Based on the current evidence, a dual-plan strategy remains the most defensible approach. A standard anatomic plan should be created first using established target and OAR objectives. A functional plan should then be generated using the same clinical intent, with additional objectives designed to reduce dose to higher-functioning lung. The functional plan should be adopted only if it preserves target coverage and conventional OAR constraints while producing a meaningful improvement in functional lung sparing.[2,4,6] A representative comparison of a standard clinical plan and a 4DCT ventilation-guided functional avoidance plan is shown in **Figure 2**, illustrating that functional sparing should be evaluated in the context of preserved PTV coverage and conventional OAR acceptability.

Several approaches to optimization have been reported, including binary contouring of "functional lung" above a chosen threshold and more graded or voxel-informed weighting strategies.[2,4-6] A key practical consideration is that no single thresholding approach has yet emerged as broadly generalizable across patients, imaging workflows, and institutions. Published studies have used different definitions of functional lung, different optimization priorities, and different levels of automation.[2,4-6] Given this variability, the literature does not currently support a universal contour-generation threshold or planning rule. Unlike PET standardized uptake value (SUV)-based workflows, 4DCT ventilation functional avoidance does not have a validated universal cutoff that reliably separates clinically actionable from nonactionable functional lung across scanners, algorithms, and patient populations. Therefore, binary high-function contours, percentile-based thresholds, and graded or voxel-weighted objectives should be prespecified within a commissioned institutional workflow rather than selected ad hoc for an individual plan.[2,4,5,17,19] Instead, institutions implementing functional avoidance should prospectively define the functional lung segmentation method, thresholding criteria, and optimization approach, and then apply these parameters consistently across patients.

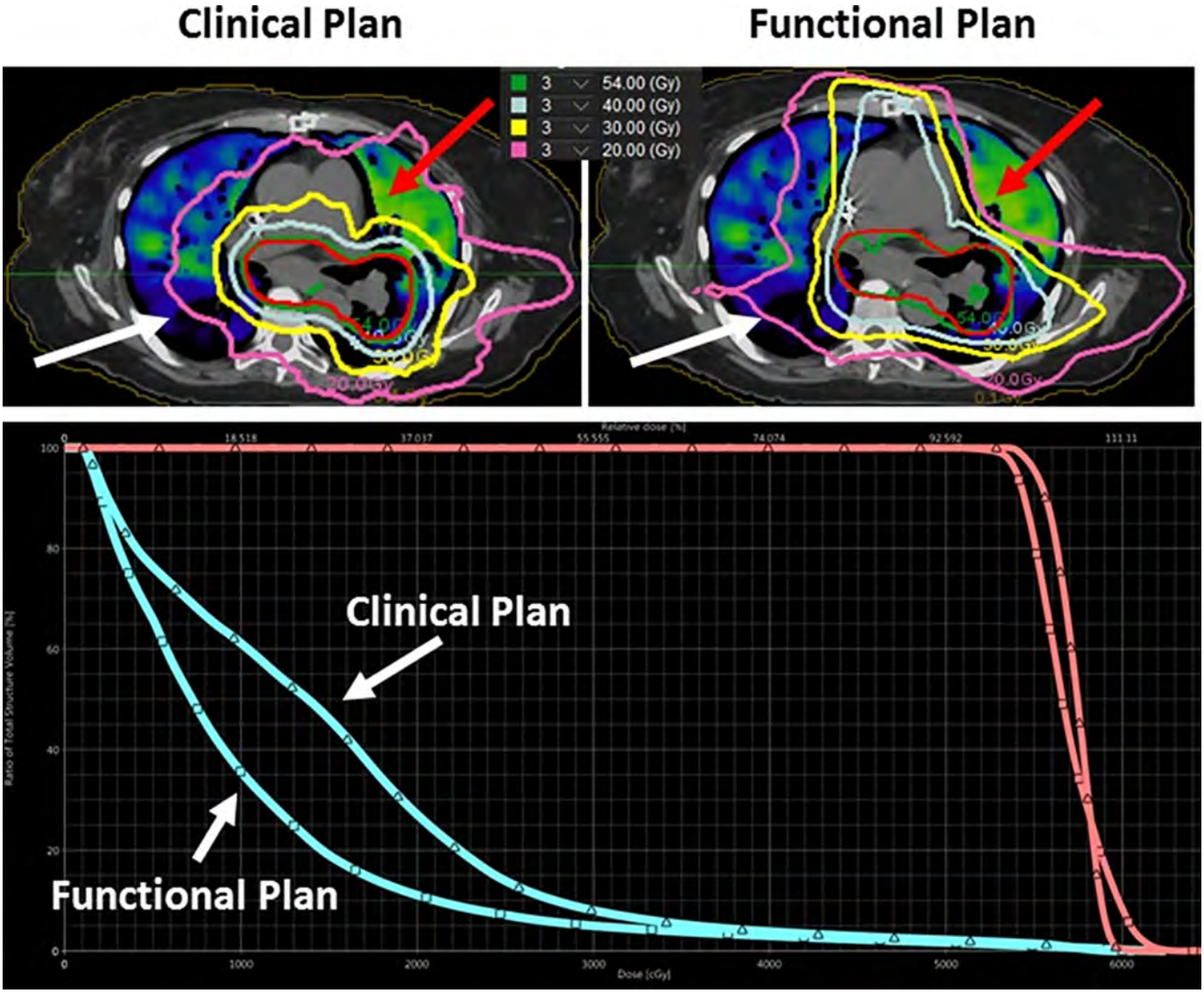
The same caution applies to dose-function metrics. Additional work evaluating dose to highly ventilated lung has further supported the association between functional dose metrics and symptomatic radiation pneumonitis, but it also reinforces that optimal functional lung constraints remain investigational rather than standardized.[3,5,25] Faught et al evaluated candidate dose-function metrics and showed that not every functional dose endpoint performs equally, particularly when functional heterogeneity is spatially complex.[5] For a clinically oriented review, the minimal reporting set should remain focused: mean lung dose and V_{20} for the standard anatomic plan; functional mean lung dose and functional V_{20} for the functional assessment; and, when low-dose bath is a relevant planning tradeoff, functional V_5 or V_{10}, defined as the functional lung volume receiving 5 Gy or 10 Gy or more, particularly for intensity-modulated radiation therapy or volumetric-modulated arc therapy.[2,4-6] Changes in PTV coverage should also be reported, along with any clinically relevant dose tradeoffs involving the heart, esophagus, spinal cord, or brachial plexus when these arise. A minimum reporting set for functional avoidance plans is provided in **Table 1**.

A further point that deserves emphasis is that functional dose reduction should not be described in isolation. A plan that lowers functional V_{20} by a few percentage points but worsens target conformity, elevates esophageal dose, or materially complicates treatment delivery may not be the right choice for an individual patient.[2,6] Functional avoidance should therefore be presented as an incremental planning strategy layered onto standard thoracic planning and not as a new competing paradigm.

Clinical Evidence

The clinical evidence is best interpreted in tiers rather than as a single uniform body of proof. Early method development, planning, and validation studies established feasibility and biologic plausibility, but they did not establish clinical benefit.[10,11,17,20-24] The strongest prospective 4DCT ventilation evidence comes from conventionally fractionated curative-intent treatment of locally advanced or stage 3 NSCLC, where functional avoidance has been associated

Figure 2. Representative comparison of a standard clinical plan and a four-dimensional CT (4DCT) ventilation-guided functional avoidance plan. The figure shows the planning CT, 4DCT ventilation overlay, isodose distributions, planning target volume, and dose-volume comparison for the functional lung contour and target. The functional plan demonstrates selective reduction of dose to better-ventilated lung while maintaining target coverage and standard planning constraints, with dose redistributed preferentially toward lower-functioning lung when clinically acceptable. Adapted/reproduced from Waxweiler et al.[24]



with measurable reductions in functional lung dose and encouraging, although not definitive, toxicity and pulmonary function signals.[6,13,14,26] By contrast, the evidence is weaker for routine use in all early stage SBRT patients, for patients without meaningful baseline functional heterogeneity, and for centers without a commissioned 4DCT ventilation and DIR QA workflow.[3,12,13,15,17,19] Therefore, the current literature supports selective consideration in appropriately chosen patients rather than universal adoption.[3,6,13-15] **Table 2** is therefore intended to separate method development and validation evidence from prospective clinical evidence, companion analyses, randomized data, and related non-4DCT functional imaging trials.

Early patient-level feasibility work demonstrated that CT ventilation-guided treatment could be delivered in practice.[23] The more persuasive evidence began with the prospective 2-institution study reported by Vinogradskiy et al in 2018. In that interim analysis, functional avoidance was feasible, reduced dose to functional lung, and showed sufficiently favorable early toxicity results to justify continued study.[6] Importantly, the trial population reflected what remains the strongest current use case: conventionally fractionated curative-intent thoracic radiation therapy rather than SBRT or palliative treatment.[6]

The multicenter phase 2 study was notable because it tested whether this approach could be exported across

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Table 1. Minimum Reporting Set for Functional Avoidance Plans

METRIC	WHY IT MATTERS	HOW TO REPORT IT	SUPPORTING EVIDENCE
Mean lung dose	Standard benchmark for thoracic toxicity risk	Report standard anatomic mean lung dose for both plans	1,2,6
Lung V_{20}	Standard benchmark with strong clinical familiarity	Report standard anatomic V_{20} for both plans	1,2,6
Functional mean lung dose	Captures dose to better-functioning lung	Report absolute value and absolute/relative change vs standard plan	2,5,6
Functional V_{20}	Most practical functional high-dose-volume endpoint	Report absolute value and change vs standard plan	2,5,6
Functional V_5 or V_{10}	Helps interpret low-dose bath with IMRT/VMAT	Report if low-dose tradeoff is relevant	4,5
Functional lung definition	Needed because thresholds are not standardized	State exact thresholding/weighting rule prospectively	2,4-6
PTV coverage	Functional gains are uninterpretable if coverage worsens	Report coverage metrics side by side	2,6
Nonlung OAR tradeoffs	Functional sparing may shift dose elsewhere	Report relevant changes in heart, esophagus, cord, and other priority OARs	2,4,6
Clinical endpoints	Dosimetry alone is insufficient	Report grade ≥ 2 pneumonitis, pulmonary function, and PROs when available	2,3,13-16

IMRT, intensity-modulated radiation therapy; OAR, organ-at-risk; PRO, patient-reported outcome; PTV, planning target volume; VMAT, volumetric-modulated arc therapy.

institutions rather than confined to a single expert center. That study reported 67 evaluable patients, an average reduction in functional lung V_{20} of 3.5 percentage points, and a grade 2 or higher pneumonitis rate of 14.9% compared with the 25% historical benchmark used in the trial design.[2] A balanced interpretation is that the study supports multicenter feasibility and provides encouraging outcome-level evidence but does not independently establish randomized superiority over standard planning.

The companion reports are useful, but should be interpreted with caution. Importantly, the Miller, Ghassemi, Lombardo, and Poiset analyses should be interpreted as companion or secondary analyses of the same prospective 4DCT ventilation functional avoidance program, or closely related trial cohort, rather than as fully independent validation cohorts.[2,14-16,26] Miller et al reported modest average declines in diffusing capacity of the lung for carbon monoxide, forced expiratory volume in 1 second (FEV1), and forced vital capacity (FVC) at 3 months, findings that the authors interpreted as qualitatively encouraging relative to historical expectations.[14] In a secondary analysis of the same prospective 4DCT ventilation functional avoidance cohort, Ghassemi et al found that dose-function metrics were associated with post-treatment PFT changes, particularly FEV1 decline, supporting their use as clinically relevant planning and reporting endpoints.[26] Lombardo et al later reported the quality-of-life results from the prospective functional avoidance program and showed that patient-reported decline still occurred, although the dosimetric associations were modest and the overall signal remained encouraging rather than definitive.[15] Poiset et al then compared patient-reported outcomes (PROs) from the functional avoidance cohort with historical thoracic radiation therapy benchmarks, including outcomes from RTOG 0617 and a PACIFIC-era comparator framework intended to reflect more contemporary chemoradiation and immunotherapy-era practice. They reported fewer clinically meaningful declines in selected patient-reported endpoints, although this comparison remained historical rather than randomized.[16] These studies strengthen the clinical plausibility of the strategy, but they remain single-arm or historical comparison data rather than level 1 proof.

The randomized phase 2 study reported by Baschnagel et al is important because it tested 4DCT ventilation functional avoidance against standard planning in a randomized setting. In the overall cohort, functional avoidance did not improve the primary endpoint, which was based on 3-month change in 4DCT-derived ventilation.[13] However, in the conventionally fractionated subgroup, functional avoidance was associated with lower grade ≥ 2 pneumonitis, 8.2% vs 32.3%, and smaller 3-month declines in FEV1 and FVC.[13] This finding should be interpreted cautiously, but it supports the view that the most promising current population may be conventionally fractionated locally advanced or stage 3 NSCLC rather than all thoracic radiation therapy patients.

Other prospective studies provide broader context without directly elevating

Table 2. Key Validation, Planning, and Clinical Evidence for Four-Dimensional CT Ventilation Functional Avoidance

STUDY	DESIGN	IMAGING/PLANNING METHOD	POPULATION	MAIN FINDING	CLINICAL RELEVANCE	LIMITATIONS
Guerrero et al[10]	Method development	Dynamic ventilation imaging from 4DCT	Technical development	Established the foundational concept of deriving ventilation from phase-resolved CT	Landmark method paper	Not a clinical validation study
Castillo et al[11]	Method comparison	Density change vs Jacobian methods	Technical development	Showed that algorithm choice affects derived ventilation	Important for understanding no interchangeability	Technical focus only
Vinogradskiy et al[20]	Clinical validation	4DCT ventilation vs nuclear medicine V/Q imaging	Patients with lung cancer	Demonstrated clinically meaningful correlation with nuclear medicine imaging	Supports biologic plausibility	Correlation, not equivalence
Yamamoto et al[21]	Clinical validation	4DCT ventilation vs PFTs and SPECT ventilation	Patients with lung cancer	Supported correlation with physiologic and imaging measures	Reinforced external validation	Method dependent
Brennan et al[22]	Clinical validation	4DCT ventilation vs PFT data	Thoracic patients	Showed relationship between 4DCT ventilation and PFT data	Supports clinical interpretability	Population-level rather than definitive patient-level truth standard
Kipritidis et al[17]	Multi-institutional validation	Comparative CT ventilation pipelines	Multi-institution study	Demonstrated algorithm dependence and lack of full standardization	Key QA and implementation relevance	Does not identify a single universally best algorithm
Vinogradskiy et al[6]	Prospective 2-institution clinical trial	4DCT ventilation-guided functional avoidance	Conventionally fractionated locally advanced lung cancer	Feasible; reduced functional lung dose; early toxicity signal acceptable	First prospective clinical workflow signal	Interim analysis; nonrandomized
Vinogradskiy et al[2]	Multicenter phase 2	4DCT ventilation-guided functional avoidance	67 evaluable patients	67 evaluable patients; mean functional V_{20} reduction 3.5 percentage points; grade ≥ 2 pneumonitis 14.9% vs 25% historical benchmark[2]	Strongest multicenter prospective 4DCT ventilation functional avoidance evidence to date	Historical benchmark, not randomized superiority
Miller et al[14]	Prospective companion analysis	PFT outcomes after functional avoidance	Trial cohort	Modest average declines in DLCO, FEV1, and FVC after functional avoidance	Useful physiologic follow-up; supports inclusion of pulmonary function endpoints	Companion analysis from related prospective cohort; not randomized proof
Ghassemi et al[26]	Secondary predictive analysis	4DCT ventilation dose-function metrics and PFT change modeling	56 patients from the prospective functional avoidance cohort	Dose-function metrics were associated with post-treatment PFT changes, particularly FEV1 decline[26]	Supports dose-function metrics as clinically relevant planning and follow-up endpoints	Secondary analysis; not randomized; early 3-mo PFT endpoint

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Table 2. continued

STUDY	DESIGN	IMAGING/PLANNING METHOD	POPULATION	MAIN FINDING	CLINICAL RELEVANCE	LIMITATIONS
Lombardo et al[15]	Prospective companion analysis	QoL after functional avoidance	Trial cohort	Patient-reported decline still occurred, dosimetric associations were modest	Adds patient-centered evidence and reinforces need for PRO follow-up	Single-arm interpretation
Baschnagel et al[13]	Randomized phase 2	4DCT ventilation functional avoidance vs standard planning	NSCLC; mixed conventional and SBRT cohort	Whole cohort did not meet primary imaging endpoint; conventionally fractionated subgroup favored functional avoidance signal	Most important randomized evidence to date; supports the conventionally fractionated subgroup as a key population for future study	Subgroup signal should be interpreted cautiously; not evidence for routine use in all thoracic RT patients
Yamamoto et al[8]	Single-arm prospective pilot	CT ventilation-guided avoidance	Lung cancer	Prospective pilot; grade ≥ 2 pneumonitis 17% vs 25% historical reference; feasible and safe but nonrandomized[8]	Supports implementation feasibility and favorable safety signal	Early phase, single-arm; historical reference
Bucknell et al[9]	Prospective functional imaging trial	^{68}Ga 4D-V/Q PET/CT-guided avoidance	Locally advanced NSCLC	Showed feasibility of V/Q-guided avoidance	Supports broader function-guided paradigm	Not a 4DCT ventilation study; does not establish the optimal role of ventilation vs perfusion or combined V/Q imaging
Poiset et al[16]	Historical comparison PRO analysis	PROs after functional avoidance compared with thoracic RT benchmarks	Functional avoidance cohort compared with historical thoracic RT benchmarks	Compared functional avoidance PROs with historical thoracic RT benchmarks; selected PRO signals favored functional avoidance, but comparison was historical rather than randomized	Helps contextualize PROs in contemporary thoracic RT practice	Related/overlapping cohort; historical comparator rather than independent randomized validation
Yaremko et al[7]	Double-masked randomized controlled trial	Hyperpolarized helium-3 MRI-guided functional avoidance	Patients with locally advanced lung cancer	Underaccrued trial; similar QoL results between arms in the published report[7]	Important comparator using a more direct functional imaging modality rather than 4DCT ventilation	Not a 4DCT ventilation study; underaccrual limits interpretation

The dosimetric and feasibility literature established that functional avoidance could be done, but the more important question is whether it changes clinically meaningful outcomes. Key validation studies, prospective clinical trials, companion analyses, and related functional imaging studies are summarized in the table.

4DCT, four-dimensional CT; DLCO, diffusing capacity of the lungs for carbon monoxide; FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; NSCLC, non-small cell lung cancer; PFT, pulmonary function test; PRO, patient-reported outcome; QA, quality assurance; QoL, quality of life; RT, radiation therapy; SBRT, stereotactic body radiation therapy; V/Q, ventilation/perfusion.

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4DCT ventilation to universal standard-of-care status. These non-4DCT studies are included as contextual comparator evidence because they use functional imaging modalities that are more directly physiologic or combined functional anatomic approaches, rather than the deformable registration-derived 4DCT ventilation surrogate emphasized in this review.[3,7,9] This broader evidence base is important because it shows that functional avoidance is being investigated across multiple institutions, imaging platforms, and trial designs, even though the strongest 4DCT ventilation data remain concentrated in a limited number of prospective cohorts.[3,7-9,13] The Functional Lung Avoidance for Individualized Radiation Therapy trial used hyperpolarized helium-3 MRI rather than 4DCT ventilation and was under accrued, with similar quality-of-life results between arms in the published report.[7] Yamamoto et al later reported a single-arm prospective pilot of CT ventilation-guided functional avoidance, supporting feasibility and safety but still in an early phase framework.[8] In that prospective pilot experience, the reported grade ≥ 2 pneumonitis rate was 17% compared with a 25% historical reference, supporting feasibility and a favorable safety signal but not establishing randomized superiority.[8] Bucknell et al showed that functional avoidance guided by ^{68}Ga-4D-V/Q PET/CT is feasible in locally advanced NSCLC, further supporting the broader concept that function-guided thoracic planning is clinically workable.[9] Collectively, these studies support the paradigm of functional imaging-informed planning, but they do not yet resolve whether ventilation-guided, perfusion-guided, or combined V/Q-guided planning is optimal, nor do they justify describing 4DCT ventilation as universally "proven."[3,4,9] Taken together, the prospective clinical data suggest a consistent but still evolving signal: 4DCT ventilation functional avoidance can reduce dose to better-ventilated lung and may reduce clinically meaningful pulmonary toxicity in selected conventionally fractionated patients.[2,6,8,13] The most useful quantitative signals are the multicenter phase 2 functional V_{20} reduction of 3.5 percentage points with 14.9% grade ≥ 2 pneumonitis, the Yamamoto prospective pilot pneumonitis rate of 17% against a 25% historical reference, and the Baschnagel conventionally fractionated subgroup result of 8.2% vs 32.3% grade ≥ 2 pneumonitis.[2,8,13] However, these data should be interpreted cautiously because available studies include single-arm designs, historical comparisons, overlapping datasets, subgroup findings, heterogeneous ventilation algorithms, and limited randomized outcome evidence.[2-4,13-17,19]

Practical Implementation Workflow

As summarized in **Figure 1**, clinical implementation should begin at simulation rather than optimization. The planning 4DCT must first satisfy the same quality standards required for a robust thoracic motion-management workflow. That includes appropriate respiratory coaching, stable phase sorting, and explicit review for artifact, mis-binning, patchy motion capture, and severe streak or truncation artifact.[4,12] If the 4DCT is not good enough for confident thoracic planning, it is not sufficient for ventilation mapping. Practical implementation steps and QA decision points are summarized in **Table 3**.

The next step is segmentation, phase selection, and deformable registration. Here, the principles of the American Association of Physicists in Medicine Task Group 132 report on image registration and data fusion in radiation therapy are directly applicable: the institution should use a commissioned registration workflow, perform patient-specific review rather than relying on the software output alone, and document how failed or suspicious registrations are handled.[19] In practical terms, this requires assessment of whether fissures, vessels, bronchi, tumor-lung interfaces, and pleural boundaries deform plausibly; whether ventilation hot and cold regions are anatomically credible; and whether apparent extreme values may instead reflect noise or artifact.[4,17,19]

Only after the map is approved should optimization proceed. A conventional plan should first be generated, followed by a functional avoidance plan, with the 2 plans compared side by side. The functional plan should be selected only if it achieves the prespecified functional sparing objective while maintaining coverage and conventional OAR acceptability.[2,4,6] This dual-plan benchmark may appear conservative, but it is the most practical way to ensure that "functional avoidance" represents a real patient-specific gain rather than a theoretical exercise.

Quality Assurance and Sources of Uncertainty

The first QA gate is respiratory imaging quality. The AAPM Task Group 76 report on respiratory motion management remains relevant because the entire 4DCT ventilation chain depends on respiratory resolved source images.[12] Irregular breathing, poor respiratory-phase sorting, inadequate phase definition, motion truncation, and severe artifact can all distort the source data and propagate into the ventilation estimate. Representative examples of patient selection and QA challenges are shown in **Figure 3**; they include heterogeneous vs homogeneous ventilation patterns, source 4DCT artifacts, and DIR- or algorithm-dependent ventilation results. The purpose of **Figure 3** is to emphasize that map review should be a clinical QA decision point: heterogeneous maps may be actionable only when the underlying image quality and registration are credible, whereas homogeneous maps, artifact-dominated scans, or algorithm-dependent extremes may be nonactionable even if a ventilation map can technically be generated. In

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Table 3. Practical Implementation and Quality Assurance Checklist

WORKFLOW STEP	KEY ACTION	PRIMARY TEAM MEMBER	QA CONCERN	WHEN TO PROCEED	STOP/REPEAT CRITERION
Patient selection	Confirm curative-intent case, functional heterogeneity likely, and plausible dosimetric opportunity	Radiation oncologist	No expected gain from functional guidance	Clear potential benefit and acceptable complexity	Homogeneous function expected or no plausible dosimetric advantage
Simulation	Acquire high-quality planning 4DCT with respiratory coaching	Therapist and simulation team	Irregular breathing, motion truncation, severe artifact	Stable respiratory trace and interpretable phases	Major artifact, mis-binning, or incomplete motion capture
Image review	Review raw 4DCT before map generation	Radiation oncologist and physicist	Poor phase sorting or anatomy distortion	Source scan acceptable for thoracic planning	4DCT not acceptable for standard clinical use
Segmentation	Confirm lung contours and exclude gross errors	Dosimetrist/ physicist with physician review	Segmentation leak, missing lung, tumor-lung boundary issues	Contours anatomically credible	Gross contour failure or unresolved ambiguity
DIR	Run commissioned deformable registration workflow	Physicist	Nonphysiologic deformation, edge failures	Deformation anatomically plausible on review	Registration clearly implausible
Ventilation map review	Inspect hot/cold regions for plausibility	Physicist and physician	Artifact-driven extremes, map-anatomy mismatch	Map pattern clinically plausible	Map dominated by artifact or unexplained extremes
Standard plan	Build conventional plan first	Dosimetrist	Baseline plan not optimized	Standard plan meets clinical goals	Baseline plan not clinically acceptable
Functional plan	Add functional objectives using same clinical intent	Dosimetrist and physicist	Functional sparing worsens coverage or OARs	Measurable functional-sparing gain with preserved clinical acceptability	Functional gain only achieved by unacceptable tradeoff
Dual-plan comparison	Compare standard vs functional plan using prespecified metrics	Physician, dosimetrist, physicist	Cherry-picking metrics	Functional plan shows meaningful net benefit	No meaningful gain or conflicting priorities
Documentation	Record map definition, QA outcome, metrics, and rationale for plan choice	Entire team	Unclear reproducibility and audit trail	Workflow and rationale fully documented	Incomplete QA or missing decision record

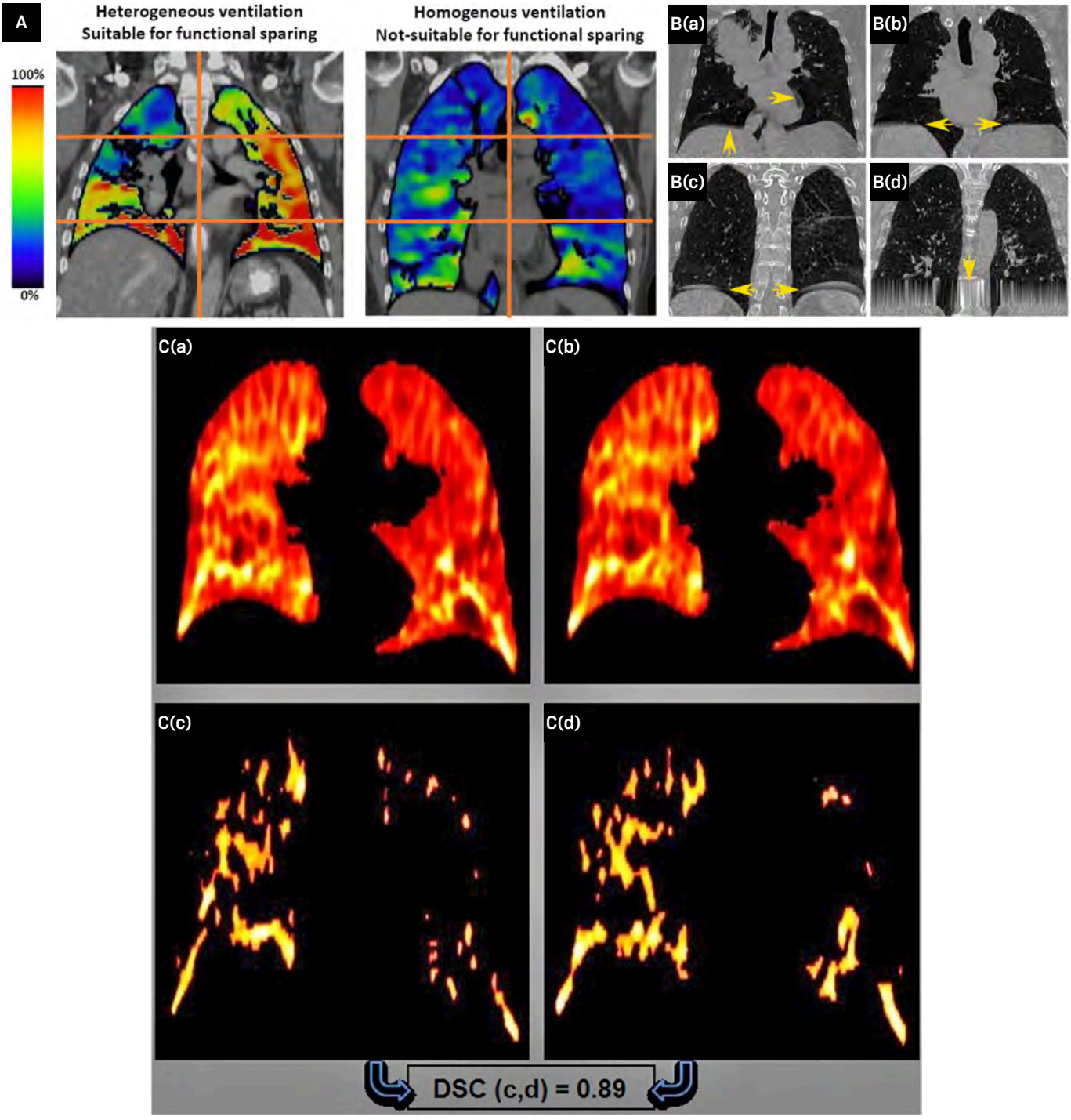
4DCT, four-dimensional CT; DIR, deformable image registration; OAR, organ-at-risk; QA, quality assurance.

practice, this means the functional map should not be used for planning when the source 4DCT is not acceptable for standard thoracic planning, respiratory-phase sorting is clearly unreliable, deformable registration is anatomically implausible, or the ventilation map is dominated by artifacts rather than credible regional lung function patterns.

The second major source of uncertainty is deformable registration. TG-132 provides the most useful radiation therapy-specific framework for acceptance testing, end-to-end validation, and patient-level review.[19] For clinical use, that should translate into a short list of operational rules: use one validated institutional workflow; track software version changes; perform patient-specific visual review of the deformation field and propagated anatomy; and reject maps that are anatomically implausible or obviously artifact dominated.[4,17,19] The literature does not support any single algorithm.

The third source of uncertainty is how the map is converted into a planning objective. Functional thresholding, binary-vs-weighted optimization, segmentation boundaries, and even whether ventilation alone is the optimal biologic target remain unsettled.[3-5] This uncertainty

Figure 3. Acceptable vs nonactionable or unreliable imaging scenarios for four-dimensional CT (4DCT) ventilation functional avoidance. Representative published examples showing key patient selection and quality assurance considerations. (A) Homogeneous and heterogeneous 4DCT ventilation patterns overlaid on standard CT. Heterogeneous ventilation may provide a stronger basis for functional avoidance than a homogeneous map. (B) Examples of 4DCT artifacts: (a) misalignment/truncation, (b) truncation, (c) duplication, and (d) interpolation artifact. (C) Algorithm-dependent 4DCT-derived ventilation results: (a) and (b) ventilation images generated using different ventilation algorithms, and (c) and (d) corresponding upper-20% thresholded ventilation volumes. These examples support patient-specific review of 4DCT quality, deformable registration, ventilation map plausibility, and functional heterogeneity before using a map for planning. Adapted from Waxweiler et al, Carrizales et al, and Latifi et al.[24,27,28]



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does not argue against the method, but it does require transparent reporting. Overstating technical certainty in an area that still lacks standardization may make the clinical argument less convincing.

Current Limitations and Future Directions

The current literature supports selective implementation, not universal adoption. Key unresolved issues include the absence of phase 3 outcome data, heterogeneity of ventilation algorithms and thresholding rules, uncertain reproducibility across newly adopting centers, and unclear incremental benefit in modern chemoimmunotherapy-era practice.[3,4,13,17] The evidence remains strongest in experienced thoracic programs with robust 4DCT acquisition, physics support, and prospective QA discipline.[2,4,13] That raises an external validity question: how well will the reported outcomes generalize to low-volume or newly adopting centers? The answer remains uncertain. In addition, much of the prospective evidence was generated before all contemporary combined modality practice patterns became routine, so the size of incremental benefit in current practice may differ from what earlier cohorts suggested.[2,4,13-16]

The maturity of adjacent areas of functional avoidance research also should not be overstated. Proton-based functional avoidance remains attractive but is still supported mainly by planning and early feasibility literature rather than robust comparative outcome data.[3,4] Adaptive functional radiation therapy is conceptually appealing because ventilation may change during treatment as tumors regress or airways reopen, but prospective evidence linking adaptive reventilation strategies to better clinical outcomes remains limited.[3,4] AI-generated ventilation surrogates may improve automation and workflow efficiency, yet current evidence is still predominantly technical or dosimetric rather than prospective clinical-outcome based.[4,29] Pulmonary perfusion imaging deserves separate consideration because ventilation and perfusion provide related but nonidentical information about regional lung function. Perfusion can be assessed using nuclear medicine approaches such as SPECT or V/Q PET/CT, and investigational CT-based approaches including dynamic contrast CT or CT-derived vascular/perfusion biomarkers. Available data support continued evaluation of perfusion-guided and combined V/Q-guided planning, but they do not yet establish whether ventilation-guided, perfusion-guided, or combined ventilation/perfusion avoidance is optimal for routine clinical implementation.[3,4,9,30,31] Accordingly, AI-based automation, adaptive functional replanning, and proton-based functional avoidance should be framed as priorities for prospective testing and workflow maturation rather than as evidence of routine clinical readiness.[3,4,29]

The next generation of trials should therefore be more selective and better targeted rather than simply broader in scope. Priority should be given to conventionally fractionated locally advanced or stage 3 NSCLC, with prospectively specified 4DCT and DIR credentialing, a compact and interpretable set of functional dose metrics, and clinically meaningful endpoints, including grade 2 or higher pneumonitis, longitudinal pulmonary function, and validated PROs, rather than imaging endpoints alone.[2-4,13-16] Comparative work between ventilation-guided and perfusion-guided strategies is still needed, and combined V/Q approaches may ultimately prove more clinically informative than ventilation alone.[3,4,9]

Conclusion

4DCT ventilation map-based functional avoidance is technically feasible, biologically plausible, and supported by a growing prospective literature.[2,6,13-18,20-23] In experienced thoracic programs that can deliver high-quality 4DCT simulation, vetted deformable registration, patient-specific map QA, and disciplined dual-plan review, the technique may be a reasonable but selective option for conventionally fractionated curative-intent lung radiation therapy, especially in locally advanced or stage 3 NSCLC with clear baseline functional heterogeneity.[2,4,13] Clinically, the technique should be viewed as an add-on to conventional thoracic planning and QA, not as a replacement for validated whole-lung, target-coverage, or nonlung OAR constraints.[1,2,4] What the literature does not yet justify is routine use in every thoracic patient or the claim that 4DCT ventilation functional avoidance is already a universal standard of care.

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REVIEW

Respiratory Motion Management in Lung Cancer Radiation Therapy: A Practical Review and Decision Framework for Technique Selection and Treatment Delivery

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Abstract

Respiratory motion remains a defining geometric and dosimetric challenge in lung radiation therapy, but not every moving target requires advanced motion control. This narrative review synthesizes existing guidance into a consequence-based clinical checklist for selecting and verifying the simplest reproducible strategy for an individual patient. The clinically relevant question is whether the observed motion is consequential for target coverage, organ-at-risk sparing, image-guidance confidence, or treatment-delivery robustness. 4-dimensional CT (4DCT) anchors motion assessment and selection of free-breathing vs managed respiratory-state workflows. For many patients, internal target volume (ITV)-based planning with robust image guidance remains an appropriate baseline strategy when motion can be safely encompassed. Escalation to breath hold, respiratory gating, or abdominal compression is best reserved for situations in which the managed state provides a patient-specific geometric or dosimetric advantage, can be reproduced consistently, and can be verified throughout treatment. External surrogates and surface guidance can support monitoring, but they do not replace internal target verification. This review summarizes 4DCT-based motion assessment, ITV-based planning, gating, breath hold, abdominal compression, surrogate monitoring, image guidance, and quality assurance, emphasizing that the preferred strategy is usually the least complex approach that preserves coverage, protects organs at risk, and can be delivered reproducibly.

Keywords: lung cancer, respiratory motion management, stereotactic body radiation therapy, 4-dimensional CT, internal target volume, respiratory gating, breath hold, abdominal compression, surface-guided radiation therapy, quality assurance

Introduction

Respiratory motion is a defining geometric and dosimetric problem in lung radiation therapy, not because every moving tumor requires an advanced intervention, but because unrecognized or poorly managed motion can compromise target coverage, enlarge normal-tissue exposure, and weaken confidence in image guidance.[1-3] The practical question is therefore not which motion-management device is most sophisticated; it is whether the observed motion is consequential for the intended plan, and whether a simpler or more selective strategy can be reproduced safely over the course of treatment.[1,4-6]

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Current practice reflects that consequence-based approach. In the American Association of Physicists in Medicine (AAPM) Task Group 324 survey, most respondents reported using respiratory motion management, but internal target volume (ITV)-based approaches remained more common than gating or tracking workflows.[1,4] That pattern is clinically reasonable: advanced methods can narrow the motion envelope in selected patients, but they also add coaching, treatment time, image-verification demands, quality assurance (QA) requirements, and additional opportunities for error.[1,5,7,8] The remaining gap is not a lack of technique-specific guidance, but rather the absence of a concise, consequence-based pathway linking simulation findings to treatment-room verification and decisions about de-escalation.

Accordingly, this review is intended for clinical teams choosing among motion-encompassing planning, respiratory gating, breath hold, abdominal compression, and surrogate-based monitoring. The central thesis is deliberately conservative: the best technique is usually the least complex approach that preserves target coverage, protects organs at risk (OARs), and can be verified and reproduced safely.[1,4,5,8] The emphasis is photon-based lung radiation therapy, including stereotactic body radiation therapy (SBRT) and conventionally fractionated treatment, with technology-specific discussion limited to workflows represented in the cited clinical and technical literature.

Respiratory Motion as a Clinical Problem

Respiratory motion becomes clinically important when it changes a decision. In practice, this may mean changing the ITV/planning target volume (PTV) approach, increasing margins, shifting from free breathing to a managed respiratory state, approaching lung V_{20}/MLD/V5 or serial-organ constraints, or reducing confidence in image registration. For a peripheral upper-lobe tumor with limited excursion, free-breathing ITV-based planning may be robust and efficient. For a lower-lobe or peridiaphragmatic lesion, tumor motion may be larger and more phase-dependent, and a motion-encompassing plan may enlarge the treated volume enough to affect lung, heart, esophagus, or proximal bronchial tree constraints.[1,2,9,10] The same measured motion also has different consequences in a 3-fraction or 5-fraction SBRT plan than in a conventional 30-fraction plan because SBRT uses high fractional dose, tight margins, and steep dose gradients.[5-7,11]

Motion uncertainty is also not confined to the planning CT. Respiratory baseline can shift, the tumor may not follow an external marker perfectly, and intrafraction variation can erode the apparent advantage of a narrow treatment window.[12-15] This is why motion management should be evaluated as an end-to-end process: simulation, contouring dataset, dose calculation, image guidance, treatment delivery, and stop rules all have to describe the same respiratory state.[1,16-18]

The clinical stakes are particularly apparent in SBRT. SBRT established high local control for medically inoperable early-stage non-small cell lung cancer, but central anatomy introduced a different risk profile, with toxicity concerns that made image guidance, dose constraints, and geometric reliability non-negotiable.[6,11,19,20] For conventionally fractionated thoracic radiation therapy, respiratory management is usually less about millimeter-scale gradient preservation and more about maintaining coverage while avoiding unnecessary lung and cardiac dose, a concern reinforced by modern data in stage III non-small cell lung cancer linking thoracic dose distributions to outcomes and toxicity.[1,10,21]

4DCT Simulation and Motion Assessment

Four-dimensional CT (4DCT) simulation and motion assessment remains the practical foundation for lung motion assessment because it provides a phase-resolved view of the target and thoracic anatomy during breathing.[3,22-24] Its value is not the production of a single motion number, but the ability to assess tumor trajectory, phase dependence, proximity to OARs, and whether respiratory motion changes the contouring or dose-calculation problem.[1,2,24]

A useful simulation is both an imaging study and a feasibility test. If breath hold, gating, or abdominal compression is being considered, the simulation should show that the selected maneuver improves geometry or dosimetry for the patient.[8,25-27] If a respiratory belt, marker block, spirometric device, or surface system will be used for sorting or delivery, the respiratory-monitoring chain should be as consistent as possible between simulation and treatment; differences between respiratory monitoring systems have been shown to matter in combined 4DCT and gated workflows.[1,17,18]

Maximum-intensity projection (MIP) can support ITV generation in selected lung lesions with adequate contrast, while average-intensity projection (AIP) images are often useful for free-breathing dose calculation. However, direct review of phase datasets remains important for tumors near the diaphragm, mediastinum, chest wall, or atelectatic lung.[24,28,29] Irregular breathing and sorting artifacts can misrepresent target excursion or shape, so a poor-quality 4DCT should not be allowed to define a narrow margin or justify a complex motion strategy without additional verification.[1,23,30] **Table 1** summarizes the practical roles, common pitfalls, and verification implications of the main 4DCT-derived datasets used in lung radiation therapy planning.

Clinical Decision Framework

A practical decision framework starts with 4 questions. (1) Is the motion real and representative? (2) Does it affect target coverage, OAR sparing, registration

Table 1. Practical Roles and Limitations of 4-Dimensional CT-Derived Datasets in Lung Radiation Therapy Planning[1,8,23,24]

DATASET OR IMAGE TYPE	PRACTICAL ROLE	MAIN ADVANTAGE	COMMON LIMITATION	VERIFICATION IMPLICATION
Phase-resolved 4-dimensional CT images	Direct review of tumor motion, trajectory, deformation, and relationship to adjacent anatomy	Best representation of respiratory motion pattern across the breathing cycle	Can be affected by irregular breathing, sorting artifacts, or poor surrogate signal	Phase images should be reviewed before relying on MIP, AIP, or reduced-margin strategies
Maximum-intensity projection	ITV generation for selected lung lesions with good tumor-to-lung contrast	Efficient visualization of the full motion envelope	Can overestimate or underestimate target extent near mediastinum, diaphragm, vessels, atelectasis, or chest wall	Should not be used blindly; confirm target boundary on phase images
Average-intensity projection	Dose calculation for free-breathing treatment in selected cases	Represents time-averaged anatomy for free-breathing dose calculation	Does not fully show motion extremes or transient tumor positions	Should be paired with appropriate target definition from phase images or ITV dataset
Mid-ventilation or mid-position dataset	Planning around a representative respiratory position when residual motion is handled by margins or image guidance	May reduce treated volume compared with full ITV approaches	Requires careful motion modeling, image guidance, and residual uncertainty assessment	Margin reduction should be justified by institutional verification and reproducibility
Breath-hold CT	Planning in a managed respiratory state, commonly DIBH	Can reduce motion and improve thoracic geometry in selected patients	Depends on reproducible breath-hold depth and patient tolerance	Treatment imaging must confirm the target in the same breath-hold state
Gated-phase or gated-window dataset	Planning around the respiratory phase or amplitude range intended for gated delivery	Narrows the treated motion envelope	Sensitive to duty cycle, baseline drift, and internal-external correlation changes	Internal target verification in the gated state is essential

AIP, average-intensity projection; DIBH, deep inspiration breath hold; ITV, internal target volume; MIP, maximum-intensity projection.

confidence, or dose-gradient robustness? (3) Does a managed respiratory state provide a meaningful gain over robust free breathing? (4) Can the patient and institution reproduce and verify that state at every fraction?[1,4,5,7] **Figure 1** translates these questions into a consequence-based pathway for selecting the least complex technique that still preserves target coverage, OAR protection, and treatment-room verifiability. If the answer to the 2nd or 3rd question is "no," escalation beyond motion-encompassing planning is often unnecessary. If the answer to the 4th question is "no," escalation may be unsafe even when the planning dosimetry looks attractive.[1,8,16,31]

The decision should not be driven by motion amplitude alone. Tumor location, fractionation, OAR proximity, pulmonary reserve, patient comfort, breath-hold capacity, breathing regularity, treatment time, staffing, and image-guidance strength all influence the safest choice.[1,4,7,21] In SBRT, the tolerance for residual geometric uncertainty is generally lower because high-dose gradients and hypofractionation magnify the consequences of a miss, especially for central tumors or targets close to serial thoracic structures.[6,7,19,20]

The resulting hierarchy is pragmatic rather than prescriptive and should be adapted to institutional equipment, team expertise, tumor visibility, patient tolerance, and treatment-room verification capability. ITV-based planning is the default when encompassing motion is dosimetrically acceptable and image guidance is robust.[1,4,5,31] Breath hold can be favored when the patient can reproduce the hold state and the plan gains meaningful lung, heart, or target-stability benefit.[8,32-34] Gating can be useful when motion is substantial, breath hold is not preferred or not feasible, and breathing is regular enough to support a clinically efficient window.[1,25,35,36] Abdominal compression is best reserved for patients in whom simulation confirms a benefit and tolerance is acceptable.[9,26,27] **Table 2** summarizes how this hierarchy plays out clinically by comparing the best-fit scenario, expected gain, verification burden, and fallback pathway for each motion-management option.

ITV-Based and Motion-Encompassing Planning

ITV-based planning remains the baseline strategy for many lung radiation therapy patients because it is robust to irregular breathing and does not require repeated breath holds or a stable duty cycle.[1,4] In

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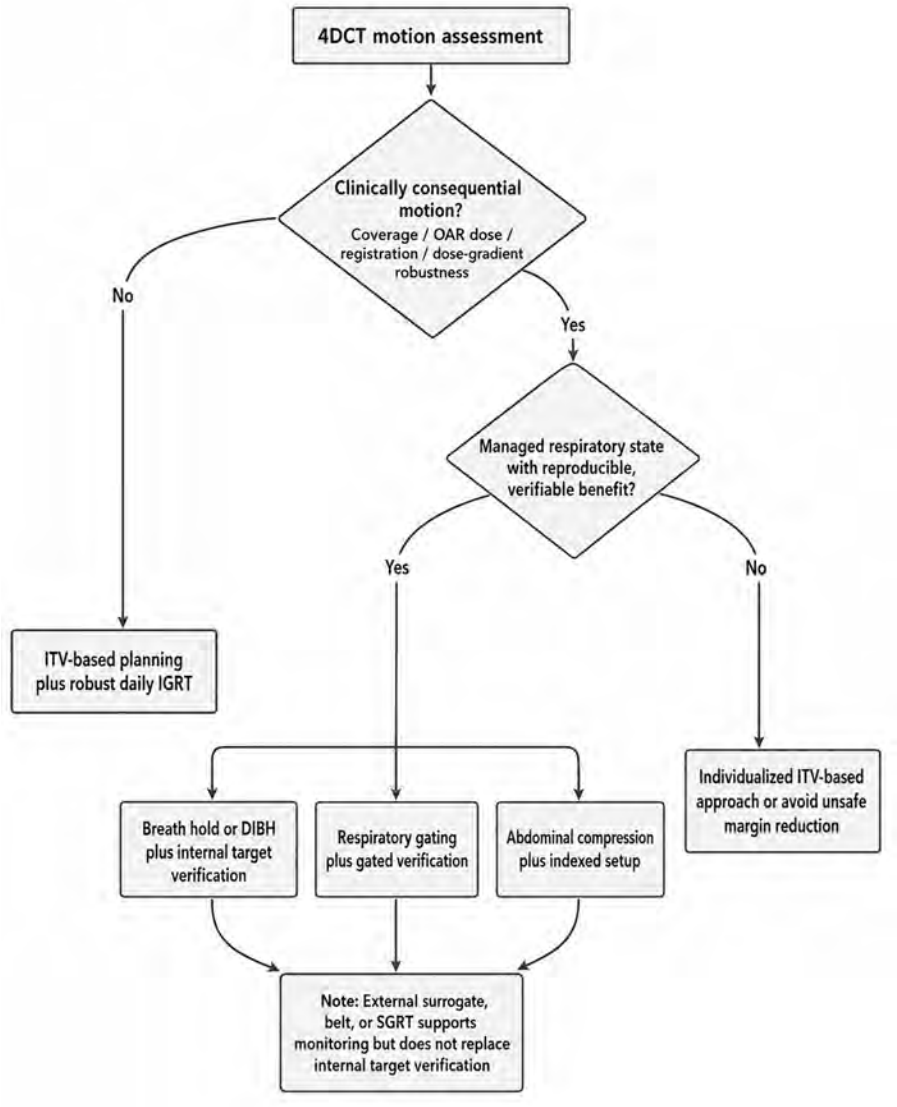
Figure 1. Consequence-based decision framework for respiratory motion management in lung radiation therapy. The figure begins with 4-dimensional CT (4DCT)-based motion assessment and asks whether respiratory motion is clinically consequential for target coverage, organ-at-risk sparing, registration confidence, or dose-gradient robustness. If not, internal target volume (ITV)-based planning with robust daily image guidance is generally favored. If motion is clinically consequential, the framework evaluates whether a managed respiratory state provides a reproducible and verifiable advantage and presents breath hold, respiratory gating, and abdominal compression as patient- and institution-specific options rather than a fixed sequence. External surrogate monitoring, including respiratory belts or surface guidance, is shown as a supportive monitoring layer rather than a substitute for internal target verification.[1,4,7,8] Abbreviations: DIBH, deep inspiration breath hold; IGRT, image-guided radiation therapy; OAR, organ at risk; SGRT, surface-guided radiation therapy.



peripheral lung SBRT, ITV-based planning remains compatible with implementation guidance when combined with appropriate immobilization, contouring discipline, and image guidance.[5,7,31] In this context, robust image-guided radiation therapy (IGRT) generally means daily cone-beam CT (CBCT) or equivalent volumetric imaging, soft-tissue or tumor matching when visible, review of adjacent bronchovascular and bony anatomy when needed, physician review for high-risk or ambiguous matches, and predefined action thresholds. Its strength is not that it is crude, but rather that it can be highly reliable when the dosimetric price of encompassing motion is acceptable.[1,4,5]

The limitation of ITV-based planning is the treated volume. If excursion is substantial, encompassing the full respiratory envelope may increase uninvolved lung dose or worsen overlap with the heart, esophagus, chest wall, proximal bronchial tree, or great vessels.[1,10,24] This tradeoff is most important when the free-breathing plan approaches OAR constraints or when the target lies near serial structures, as in central SBRT.[6,7,19,20] A motion-encompassing approach is therefore a decision to accept a larger but robust envelope, not a reason to relax image guidance or QA.[1,16,31]

MIP-based ITV construction and related derived datasets should be used with attention to lesion visibility and anatomy. Underberg et al support MIP use for selected lung targets, but Borm et al highlight that MIP and AIPs can differ from the actual moving target representation depending on size, contrast, and motion.[24,28,29] Mid-ventilation and other motion-representative strategies may reduce margins in selected workflows, but they require a validated residual-uncertainty model and strong treatment-room verification. Clinical validation and institutional experience remain important when margin reduction is used; Bellec et al specifically evaluated ITV vs mid-ventilation in lung SBRT using in-treatment 4D-CBCT and framed margin adequacy as an image-guided question.[37-40]

Respiratory Gating

Respiratory gating restricts beam delivery to a selected respiratory phase or amplitude window, so treatment occurs within a narrower motion envelope than unrestricted free breathing.[1,35,36] The technique is most defensible when the observed motion is large enough to matter, the gating window produces

Table 2. Clinical Decision Cues for Selecting a Respiratory Motion-Management Strategy[1,4,7,8]

CLINICAL SCENARIO	USUALLY FAVORED APPROACH	WHY IT FITS	MAIN CAUTION	FALLBACK IF NOT REPRODUCIBLE
Limited tumor motion and acceptable free-breathing dosimetry	ITV-based or motion-encompassing planning	Robust, efficient, and less dependent on patient coaching	Do not assume motion is limited if 4DCT quality is poor	Repeat or supplement motion assessment if uncertainty is high
Irregular breathing, cough, anxiety, or poor coaching tolerance	ITV-based planning with robust IGRT	More reliable than complex techniques that require reproducibility	Larger treated volume may increase OAR dose	Use conservative margins and daily image guidance
Large motion with reproducible breath hold and meaningful dosimetric gain	Breath hold or DIBH	Can reduce motion and may improve lung or cardiac sparing	Benefit must persist beyond simulation and coaching	Revert to ITV or gating if breath hold becomes inconsistent
Large motion, no reliable breath hold, but regular coached breathing	Respiratory gating	Narrows beam delivery to a selected respiratory window	Duty cycle, latency, and baseline drift may reduce benefit	Use ITV-based approach if gated delivery becomes inefficient or unstable
Lower-lobe or peridiaphragmatic lesion with compression benefit at simulation	Abdominal compression as adjunct	May reduce motion envelope or improve planning geometry while preserving free breathing	Benefit is patient specific, and tolerance may be limited	Remove compression and use ITV or another verified strategy
Reliable external monitoring, but uncertain internal-external correlation	Surrogate-assisted workflow with internal image verification	Useful for coaching, sorting, gating, or breath-hold monitoring	External signal does not equal tumor position	Avoid margin reduction based on surrogate trace alone
Central or ultracentral SBRT with steep gradients near critical structures	Individualized approach with strong IGRT and conservative uncertainty management	Small geometric errors may have high clinical consequence	Overly aggressive margin reduction can be unsafe	Prefer reproducible, verifiable technique over theoretically optimal technique
Conventional fractionation with acceptable dosimetry	ITV-based planning or simple motion-encompassing strategy	Efficiency and reproducibility may outweigh marginal geometric gains	Daily setup and anatomy changes still matter	Escalate only if motion clearly compromises coverage or OAR sparing

4DCT, 4-dimensional CT; DIBH, deep inspiration breath hold; IGRT, image-guided radiation therapy; ITV, internal target volume; OAR, organ at risk; SBRT, stereotactic body radiation therapy.

a meaningful geometric or dosimetric advantage, and the patient can maintain a reproducible respiratory pattern that supports an acceptable duty cycle.[1,25,36,41] In practice, the selected gate should balance residual-motion reduction with treatment efficiency and should be verified with fluoroscopy, respiratory-correlated CBCT, or another institutional imaging strategy when feasible. Saito et al found that 3-dimensional and craniocaudal clinical target volume (CTV) motion and craniocaudal CTV position were predictive of lung-dose reduction from respiratory gating, supporting selective rather than routine use.[25]

The main weaknesses of gating are operational and related to verification. Beam-on efficiency can decrease, treatment time can increase, and the workflow is vulnerable to latency, baseline drift, irregular breathing, and changes in internal-external correlation.[14,15,36,41] A smooth external trace is not enough; gated treatment still leaves residual internal motion and requires confirmation that the internal target is in the intended state.[13-15,42] This helps explain why gating is less common than ITV-based planning in practice, despite clear value in selected patients.[1,4]

For conventional fractionation, gating may be considered when a narrower motion envelope materially improves lung or heart dosimetry without creating an impractical workflow.[1,10,25] For SBRT, gating can be attractive for larger excursions or lower-lobe/peridiaphragmatic targets near abdominal OARs when breath hold is not preferred or not feasible, but the team should explicitly account for residual motion in the gate, image-registration uncertainty, and the consequences of a missed fraction-level setup.[5,7,40,43] Gating should be abandoned or de-escalated when the patient cannot maintain a stable pattern or when verification shows that the internal target does not match the external signal.[1,14,15]

Breath-Hold Techniques

Breath-hold techniques replace cyclic respiratory motion with repeated stable respiratory states during which imaging and treatment are performed.

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Active breathing control and deep inspiration breath hold (DIBH) have long been studied as methods to reduce breathing motion and, in some patients, alter thoracic geometry favorably.[32,33,44,45] Modern implementation guidance emphasizes that breath hold is a workflow, not just a patient instruction: coaching, reproducibility testing, imaging in the hold state, and fallback criteria are required.[8,44] End-exhale breath hold and adjuncts such as supplemental oxygen may be used in selected institutional workflows, but patient comfort, achievable hold time, reproducibility, and system compatibility should be confirmed before treatment.

DIBH may be considered when it improves the relationship among the tumor, functional lung volume, heart, subcardiac structures, and, in selected lower-lobe or peridiaphragmatic cases, nearby abdominal OARs. Early lung tumor studies showed potential value for immobilization and dose distribution, and contemporary lung cancer dosimetric data suggest that selected patients may have improved pulmonary, cardiac, and subcardiac metrics compared with free breathing.[32-34] These are dosimetric and workflow advantages, not proof that DIBH is universally superior to ITV or gating; the benefit has to be demonstrated for the individual patient and reproduced over the full fraction and across fractions, with internal target confirmation in the intended hold state.[8,21,34]

Patient selection is the limiting factor. Dyspnea, cough, pain, anxiety, cognitive barriers, or inability to reproduce depth can make a nominally attractive DIBH plan less safe than a robust free-breathing plan.[1,8,44] For SBRT, repeated short holds may be feasible for some patients, but treatment time, image acquisition, and intrafraction verification must be planned around the actual hold length and reproducibility rather than around an idealized simulation performance.[7,8,31,32] For conventionally fractionated therapy, DIBH may be especially worth testing when cardiac or subcardiac sparing is a major planning objective.[10,34]

Abdominal Compression

Abdominal compression is intended to limit diaphragmatic excursion and thereby reduce respiratory motion or improve planning geometry while preserving a free-breathing workflow.[1,9,26] It can be attractive for selected lower-lobe or peridiaphragmatic lesions when breath hold is not feasible and gating would add disproportionate complexity. However, compression should not be assumed to reduce motion; when feasible, benefit can be assessed with fluoroscopy or by comparison with an uncompressed condition, recognizing that a second 4DCT may be reserved for cases with excessive residual motion.[9,26,27]

The evidence supports a patient-specific view. Negoro et al described motion reduction and setup considerations with an immobilization approach, while Heinzerling et al showed that tumor and organ motion can vary at different compression levels.[9,26] Qi et al reported that abdominal compression did not uniformly reduce target motion amplitude in peripheral lung stereotactic radiation therapy, although geometric volumes such as internal gross tumor volume and PTV could decrease.[27] Clinically, that means compression may still be useful if it improves the plan, but the endpoint should be reproducible benefit, not simply the presence of a compression device.[1,26,27]

Tolerance is part of the treatment technique. Compression that causes pain, reflux, nausea, dyspnea, respiratory distress, or increases discomfort, worsens breathing regularity, or changes patient position can create more uncertainty than it removes.[1,9,26] If compression is used, the setup should be indexed, the pressure or device position documented, and daily imaging reviewed with the same caution used for any other motion-managed state.[7,16,26,31]

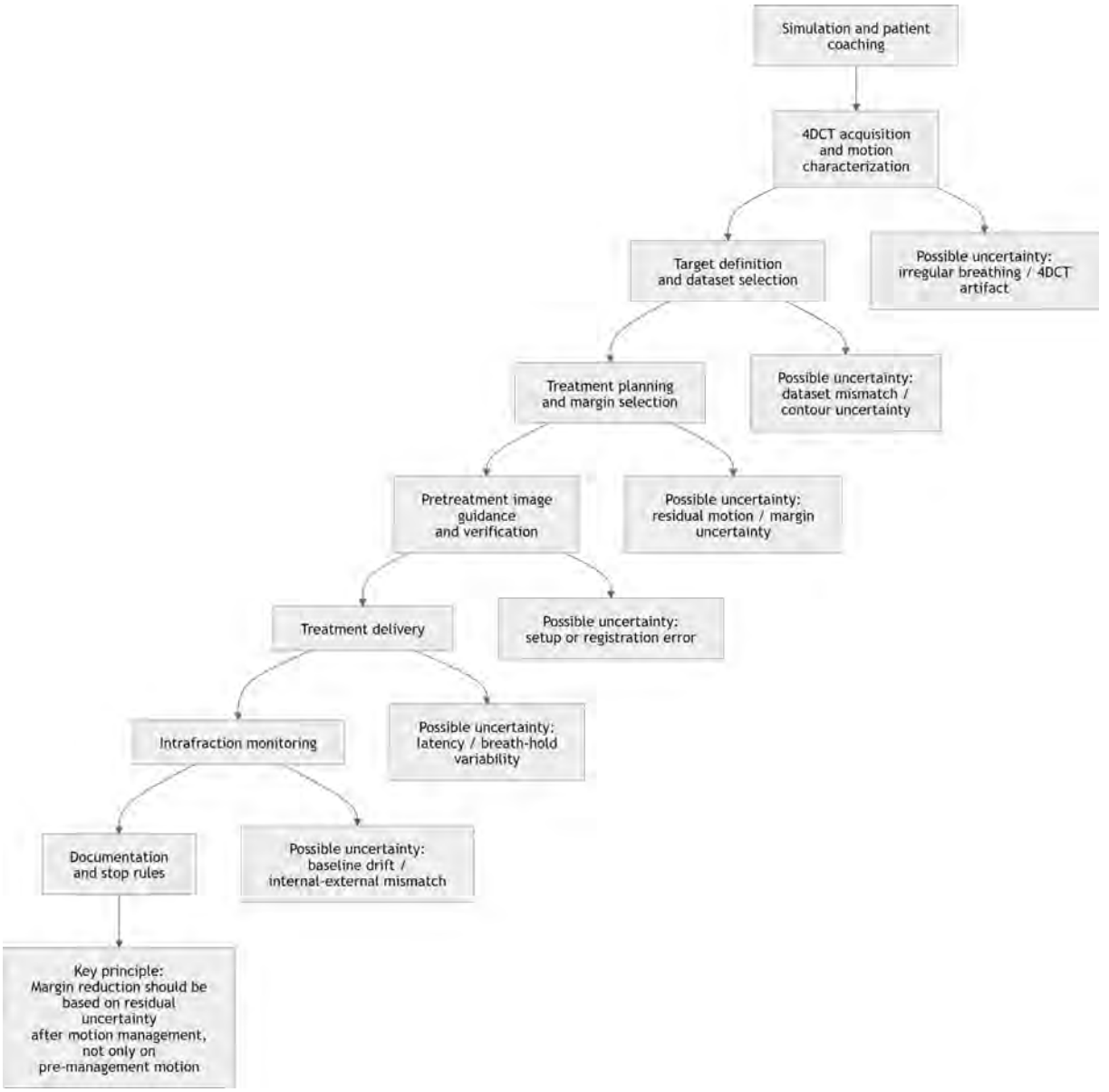
External Surrogates, Respiratory Belts, and Surface-Guided Monitoring

External respiratory signals are enabling tools. Marker blocks, belts, spirometry, and surface-guided platforms can support 4DCT sorting, coached breathing, breath-hold monitoring, gating, and intrafraction observation, but they do not directly localize the lung tumor.[1,12,13,17] Studies of external surrogates and internal-external correlation show that diaphragm or surface motion may correlate imperfectly with tumor position and may vary by patient, anatomy, respiratory phase, and time.[12-15] When a surrogate is used for gating, breath hold, or margin reduction, internal-external correlation should be established at simulation using available internal imaging and monitored during treatment for baseline drift, hysteresis, trace changes, or mismatch on repeated imaging.[13-15,40]

This limitation is most important when the surrogate is used to justify a smaller treatment envelope. Residual tumor motion can persist within a gated window, and internal-external correlation can degrade through baseline drift, hysteresis, fatigue, or cough.[14,15,42] Respiratory-monitoring systems also should not be interchanged casually between simulation and treatment, because system differences can affect the signal used for sorting or gating.[1,18] The safest operational rule is simple: the more indirect the signal, the stronger the internal-image verification should be.[16,17,40,43]

Surface-guided radiation therapy (SGRT) adds useful nonionizing information about patient surface position and intrafraction change, and AAPM Task Group (TG)-302 provides a framework for SGRT commissioning, QA, and clinical use.[17] In lung and abdominal SBRT workflows, SGRT has been used with IGRT for setup support and intrafraction monitoring, and frameless surface-guided positioning has been evaluated for lung SBRT.[46,47] The key word is with: surface guidance can

Figure 2. Residual uncertainty across the simulation-to-treatment workflow. Conceptual workflow showing how residual uncertainty can enter at multiple stages of motion-managed lung radiation therapy, including simulation, 4-dimensional CT (4DCT) acquisition, target definition, dataset selection, treatment planning, image guidance, treatment delivery, intrafraction monitoring, and documentation. Sources of uncertainty include irregular breathing, 4DCT artifact, dataset mismatch, setup error, registration uncertainty, baseline drift, system latency, imperfect internal-external correlation, breath-hold variability, and intrafraction motion. The figure emphasizes that margin reduction should be based on residual uncertainty after motion management, not simply on pre-management tumor motion amplitude.[1,8,14-18,31,40,42,43,48,49]



strengthen the workflow, but it should not replace internal target verification when respiratory motion or tumor position is the clinical question.[17,40,46,47]

Image Guidance, Verification, and QA

Image guidance is the clinical test of whether the planned respiratory strategy is being delivered. CT-based IGRT QA recommendations and lung SBRT implementation guidance emphasize localization accuracy, consistent imaging protocols, and documented action thresholds.[5,7,16,31] For motion-managed lung treatment, the team should define in advance which dataset is the reference, which anatomy is registered, how residual motion is handled, and what degree of mismatch triggers re-coaching, re-imaging, adaptation, or technique de-escalation.[1,8,16,31] **Figure 2** maps this end-to-end alignment from simulation through delivery and highlights the stages at which residual uncertainty can enter the workflow.

CBCT, respiratory-correlated CBCT, and 4D-CBCT can provide treatment-room information that a planning 4DCT cannot. Sonke et al and Li et al established technical approaches for

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Table 3. Workflow and Quality Assurance Checklist for Motion-Managed Lung Radiation Therapy[1,8,16,17]

WORKFLOW STAGE	KEY QUESTION	TECHNIQUE-SPECIFIC CHECKS	STOP-RULE TRIGGER
Simulation	Can the patient tolerate the intended position and respiratory maneuver?	Assess comfort, coaching response, breathing regularity, breath-hold ability, and compression tolerance	Patient cannot reproduce the intended state or tolerate setup
4DCT acquisition	Is the 4DCT representative of treatment breathing?	Review breathing trace, sorting quality, artifacts, tumor visibility, and phase consistency	Severe artifact, irregular breathing, or unreliable surrogate signal
Target definition	Is the target dataset appropriate for the selected strategy?	Confirm phase images, MIP/AIP use, ITV construction, breath-hold CT, or gated-window dataset	Target boundary uncertain or dataset does not match intended treatment condition
Treatment planning	Does the motion strategy meaningfully improve coverage or OAR sparing?	Compare free-breathing and managed-state dosimetry when relevant	Added complexity produces no meaningful geometric or dosimetric benefit
Pretreatment imaging	Is the internal target confirmed in the intended respiratory state?	Verify target position with CBCT, 4D-CBCT, fluoroscopy, or other available imaging	Target mismatch exceeds institutional action threshold
Respiratory gating	Is the gating window stable and efficient?	Check duty cycle, latency, baseline drift, audiovisual coaching, and gated-state imaging	Unstable trace, poor duty cycle, or loss of reproducible gating window
Breath hold/DIBH	Is the breath hold reproducible during treatment?	Verify breath-hold depth, duration, surface or spirometric signal, and image guidance in hold state	Inconsistent hold depth, short hold duration, or target mismatch
Abdominal compression	Is the compression setup reproducible and beneficial?	Confirm indexed setup, patient comfort, respiratory pattern, and target position	Discomfort, altered breathing, or no reproducible geometric benefit
Surrogate or SGRT monitoring	Does the external signal remain reliable?	Check camera/belt/marker calibration, thresholds, baseline drift, and correlation with internal imaging	External trace changes without confidence in internal target position
Documentation	Can another team member reproduce the workflow safely?	Record setup, respiratory instructions, imaging match criteria, thresholds, and fallback plan	Missing or ambiguous instructions in the treatment chart

AIP, average-intensity projection; CBCT, cone-beam CT; 4D-CBCT, 4-dimensional cone-beam CT; 4DCT, 4-dimensional CT; DIBH, deep inspiration breath hold; ITV, internal target volume; MIP, maximum-intensity projection; OAR, organ at risk; QA, quality assurance; SGRT, surface-guided radiation therapy.

respiratory-correlated or 4-dimensional CBCT, while Purdie et al and Bissonnette et al showed the value of CBCT-based localization and intrafraction or interfraction motion assessment in lung SBRT.[40,43,48,49] These tools are especially important when the plan uses tight margins, central anatomy, gating, breath hold, compression, or mid-ventilation assumptions.[7,39,40,43]

QA should match technique complexity. An ITV-based plan requires accurate 4DCT acquisition, contour review, dose-calculation dataset selection, and daily image guidance.[1,5,16] Gating requires end-to-end tests of the gating interface, latency, audiovisual coaching or monitoring, and image verification in the gate.[35,36,41,50] Breath hold requires reproducibility checks and imaging in the hold state, with triggered or repeated imaging considered in compatible workflows when the target is visible and clinically warranted, while SGRT requires commissioning and routine QA of cameras, calibration, thresholds, and workflow integration.[8,17,46,47] Linac and image-guidance QA frameworks remain the floor on which all of these motion-specific tests are built.[16,50] **Table 3** summarizes these technique-specific verification expectations, intrafraction monitoring priorities, and stop-rule triggers so that escalation remains reversible if the selected workflow is not reproducible in the treatment room.

A practical QA culture also includes stop rules. Therapists should know when to pause for unstable breathing, failed breath hold, loss of surface signal, unexpected CBCT position, or patient discomfort. Physicians and physicists should know when to accept residual uncertainty and when to resimulate or simplify the plan.[1,8,16,17] The safest escalation strategy is reversible: if the selected technique is not reproducible at treatment, the team should be able to return to a validated, usually less complex alternative.[1,4,31]

Future Directions

The evidence base would be more clinically useful if future studies reported not only motion reduction, but also residual uncertainty, treatment time, image-guidance workload, failure rates, patient tolerance, staff burden, and dosimetric consequences after realistic verification.[4,25,27,34] Head-to-head clinical outcome data comparing ITV, gating, breath hold, compression, and SGRT-assisted workflows remain limited, so broad claims of superiority should remain restrained.[4,8,25,34]

MR-guided, adaptive and motion-resolved workflows will likely continue to improve, but implementation should remain consequence-based. More imaging does not automatically produce safer treatment unless the information changes a decision and is incorporated into margins, delivery, and QA.[16,17,40,48] This review intentionally leaves 4DCT ventilation-based functional avoidance outside the main discussion; it is a separate planning objective and should not be conflated with respiratory-state selection unless a protocol explicitly integrates both questions.

The most practical future direction may be standardization rather than novelty: clearer reporting of respiratory state, surrogate type, gating window, breath-hold reproducibility, compression setting, imaging dataset, registration method, and residual uncertainty.[1,8,16,17] Such reporting would make it easier for radiation oncologists, physicists, dosimetrists, and therapists to judge whether a technique worked because it was intrinsically better or because it was selected carefully, verified rigorously, and executed reproducibly.[4,5,7,21]

Conclusion

A practical rule for lung motion management is to measure the motion, judge its consequence, choose the simplest reproducible strategy, verify the internal target, and define when to stop or de-escalate. Motion should be measured, usually with interpretable 4DCT, and then judged by its consequences for coverage, OAR sparing, image guidance, and delivery robustness.[1-3,23] ITV-based planning remains the usual baseline when motion can be encompassed safely. Breath hold, gating, and abdominal compression are valuable when they provide a patient-specific gain that can be reproduced and verified.[4,5,8,25]

External surrogates, respiratory belts, and surface monitoring can improve workflow awareness, but they are not substitutes for internal target verification.[13,14,17,46] Across SBRT and conventionally fractionated lung treatment, the most defensible technique is usually the least complex approach that preserves target coverage, protects OARs, and can be delivered safely by the team every day.[1,4,7,16]

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Practice Changes and Geographic Reach of Postprostatectomy Radiation Therapy After NRG-GU003

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Abstract

Objective: Moderately hypofractionated postprostatectomy radiation therapy (HYPORT) is an accepted practice supported by the landmark trial NRG-GU003 that established noninferiority compared to conventionally fractionated radiation therapy (COPORT) in terms of patient-reported toxicity. HYPORT is purported to increase access to postprostatectomy radiation therapy (PPRT) with fewer treatment visits and reduced burden to patients. We hypothesized the introduction of HYPORT at our institution in March 2024 increased the utilization of PPRT in the following year compared to the prior year.

Methods: 86 consecutive patients who received COPORT or HYPORT from March 2023 to April 2025 at a single, multisite institution in California by multiple treating radiation oncologists were retrospectively analyzed. Demographic, disease, and treatment characteristics were collected. Subgroup analyses were stratified by treatment regimen and by RT initiation before vs after the March 2024 publication of NRG-GU003. Statistical tests included 2-sample *t* tests, Fisher exact tests, χ^2 tests, Mann-Whitney *U* tests, and regression analyses.

Results: No significant differences in patient demographics aside from margin status were observed between patients treated before vs after March 2024. Patients treated after March 2024 were more likely to receive HYPORT regimens (2.2-2.6 Gy fractions) than those treated before March 2024 (71% vs 38%; $P < .01$). On multivariable logistic regression, treatment after March 2024 was associated with higher odds of HYPORT receipt after adjustment for facility, margin status, and age (OR 12.85; $P < .001$) and after additional adjustment for treating physician (OR 13.70; $P < .001$). Treated PPRT case volume was numerically higher after March 2024 (50 vs 36 patients), and patients treated with HYPORT traveled numerically greater distances than those treated with COPORT.

Conclusion: Adoption of HYPORT at our institution was associated with a marked increase in the use of hypofractionated treatment regimens following publication of NRG-GU003. Although institutional PPRT case volume and travel distance were numerically greater after HYPORT implementation, these findings warrant confirmation in larger studies to determine whether shorter treatment regimens improve access to care.

Keywords: postprostatectomy radiation therapy, hypofractionated radiation therapy, patient access, genitourinary cancers

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Data sharing statement: Data are available upon reasonable request. The deidentified patient-level data underlying the findings of this study may be made available from the corresponding author, Mark K. Buyyounouski, MD, MS (mbuyyou@stanford.edu), upon reasonable request and subject to institutional review, applicable patient privacy protections, and data-use requirements. Analytical code and additional study materials may also be made available upon reasonable request, where permitted. No specific reuse license applies; any approved reuse will be subject to the terms of the applicable data-use agreement and institutional policies.

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Introduction

Postprostatectomy radiation therapy (PPRT) is an important risk-adapted adjuvant therapy for prostate cancer. Its role and timing have evolved substantially following contemporary randomized trials evaluating adjuvant vs early salvage radiation therapy (RT). While no significant differences have been demonstrated in event-free or biochemical progression-free survival, early salvage RT has been found to have lower rates of genitourinary toxicity and is thus supported as a treatment option, which may spare men from RT and associated toxicities.[1-4] However, in addition to clinical factors, receipt of PPRT in routine practice may also be shaped by nonclinical and system-level factors, such as physician practice patterns, patient preference, treatment duration, and access-related barriers, such as residential location. Distance from treatment facilities has been associated with prostate cancer treatment selection more broadly,[5,6] including lower likelihood of receiving radiation compared with radical prostatectomy among patients living farther from treatment centers.[7] However, whether similar distance-related barriers influence receipt and delivery of PPRT remains less well characterized.

Hypofractionation may increase access to PPRT by reducing the logistical and financial burdens of treatment.[8-10] Conventional regimens require several weeks of daily therapy, which may be challenging not only for patients in rural areas but also for those in large, geographically dispersed urban regions where travel is time-consuming and costly. By shortening the overall treatment course and decreasing cumulative travel demands, missed work, and related out-of-pocket expenses, hypofractionated approaches can make RT more feasible and accessible for a broader group of patients.[9,11]

NRG-GU003 was the first prospective randomized clinical trial that compared hypofractionated (62.5 Gy in 25 fractions) and conventionally fractionated (66.6 Gy in 37 fractions) RT in patients receiving PPRT.[12] Hypofractionation demonstrated noninferiority, in terms of patient-reported genitourinary or gastrointestinal adverse effects at 2 years, in addition to biochemical control. These findings supported hypofractionation as a potential radiation regimen in the postprostatectomy setting.

In this study, we evaluate changes in clinical practice for PPRT after the publication of the NRG-GU003 trial by examining their impact on patient access and geographical reach, measured through the number of patients treated, the adoption of conventional vs hypofractionated regimens, and the distances patients traveled. While the NRG-GU003 trial primarily assessed treatment-related toxicity and efficacy outcomes, this study uniquely expands upon these findings by investigating real-world implementation patterns.

Methods

The study retrospectively reviewed 86 consecutive patients who underwent PPRT at a multi-site institution in California between March 2023 and April 2025. The primary endpoint was the shift in radiation modality practices following the publication of the NRG-GU003 trial. The secondary endpoint evaluated the change in the geographic reach of treatment, assessed using patients' travel distance from their primary residence to the treating facility.

Eligibility criteria included biopsy-proven prostate cancer (at initial diagnosis) and completion of PPRT at one of the institution's sites. While patients receiving salvage and adjuvant RT represent distinct clinical populations, both subsets were included in the study cohort to capture the breadth of PPRT adoption across practice settings. Demographic data were collected from the electronic health record and survey, including age, gender, race, ethnicity, and miles between residence and treatment facility calculated as driving directions on Google Maps. For patients who resided in temporary accommodations during treatment, the primary residence was used for all analyses because it was more consistently documented across the cohort and provided a standardized measure of geographic access. This approach also better captured the potential influence of shorter hypofractionated treatment regimens on access to care, as patients traveling longer distances may be more willing to arrange temporary lodging when treatment can be completed in fewer fractions. Clinical data, including start and end dates of RT, total dose prescribed, and number of fractions prescribed, were also recorded. Institutional review board approval and waiver of informed consent were obtained for this study.

Demographic, clinical, and treatment characteristics were compared between patients who initiated RT before March 1, 2024, and those who initiated treatment after this date, corresponding to the publication of the NRG-GU003 trial. Continuous variables were compared using 2-sample *t* tests or Mann-Whitney *U* tests based on distribution. Categorical variables were compared using the χ^2 test or Fisher exact test, as appropriate. The association between treatment period and receipt of hypofractionated postprostatectomy radiation therapy (HYPORT) was evaluated using multivariable Firth penalized logistic regression, adjusting for treatment facility, surgical margin status, and age. Treating physician was added as a covariate in a sensitivity analysis. Travel distance by treatment regimen was evaluated using median (quantile) regression adjusted

for treatment facility, with a log-linear model used in a sensitivity analysis. Odds ratios (ORs) are reported with 95% profile likelihood confidence intervals (CIs). All statistical tests were 2-sided, and statistical significance was defined as $P < 0.05$. Analyses were performed using R version 4.6.0 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Eighty-six patients were eligible for this study; their demographic, disease, and treatment characteristics are summarized in **Table 1**. The mean age of the overall study cohort was 69.1 years (range, 54.5-83.3). Most patients were White (63%), followed by Asian (20%) and Black or African American (7%); 8% identified as Hispanic or Latino. Patients received prostate bed irradiation to total doses of 62.5 to 75 Gy delivered in 25 to 35 fractions (2.0-2.6 Gy per fraction), with elective pelvic lymph node irradiation, when indicated, to 50 to 54 Gy in 25 to 35 fractions (1.5-2.0 Gy per fraction). Most patients (98%) received irradiation to both the prostate bed and pelvic lymph nodes, while the remaining patients received prostate bed irradiation alone. Sixty-nine (80%) patients received hormone therapy at the discretion of the treating physician. The median distance from patients' residences to their treatment facilities was 19.4 miles (range, 1.4-538.0). Three patients whose primary residences were out-of-state temporarily resided at accommodations closer to the treatment center during treatment; these patients were included in all travel distance analyses based on primary residence.

When stratified by the RT start date before and after March 1, 2024, there were no significant differences in patient demographics, including age, race, or ethnicity, between the 2 patient cohorts. Among patients treated with PPRT during the study period, a greater number was treated after March 1, 2024, compared with before March 1, 2024

Table 1. Demographic, Disease, and Treatment Characteristics

	BEFORE MARCH 2024 (N = 37)	MARCH 2024 AND AFTER (N = 49)	*P* VALUE
Age (y)			
Mean (SD)	69.19 (6.83)	69.04 (6.08)	.9[a]
Race, n (%)			.4[b]
Caucasian	21 (57%)	33 (67%)	
Non-Caucasian	16 (43%)	16 (33%)	
Ethnicity, n (%)			.5[b]
Hispanic or Latinx	4 (11%)	3 (6%)	
Not Hispanic or Latinx	33 (89%)	46 (94%)	
ISUP grade group, n (%)			.4[c]
1	5 (14%)	1 (2%)	
2	13 (35%)	23 (47%)	
3	11 (30%)	13 (27%)	
4	1 (3%)	2 (4%)	
5	7 (19%)	10 (20%)	
T stage (p), n (%)			.06[b]
1	4 (11%)	0 (0%)	
2	9 (24%)	18 (37%)	
3	24 (65%)	31 (63%)	
N stage (p), n (%)			
0	35 (95%)	46 (94%)	
1	2 (5%)	3 (6%)	
M stage (c), n (%)			
0	37 (100%)	49 (100%)	
Margin status, n (%)			.03[c]
Positive	25 (68%)	22 (45%)	
Negative	12 (32%)	27 (55%)	
Pre-RT PSA (ng/mL)			.8[d]
Median	0.04	0.07	
Range	0.009-0.77	0.007-2.13	
Total RT dose, n (%)			.004[d]
<70 Gy	13 (35%)	33 (67%)	
≥70 Gy	24 (65%)	16 (33%)	
RT no. of fractions, n (%)			.002[d]
25	13 (35%)	34 (69%)	
35	24 (65%)	15 (31%)	
Distance between patient residence and treatment facility, n (%)			.6[d]
Mean (SD)	27.5 (25.5)	36.8 (78.7)	

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(57% vs 43%, respectively), although this difference in treated case volume was not statistically significant and should be interpreted in the context of slightly unequal observation periods. However, significant differences in the RT regimen were observed; patients treated after March 1, 2024, were more likely to receive HYPORT than those treated before this date (unadjusted OR 4.04, $P = .002$). This association remained significant after adjustment for facility, age, margin status, and treating physician (adjusted OR 12.85-13.70, both $P < .001$). Neither age nor margin status independently predicted treatment regimen.

Patients treated on or after March 1, 2024, lived a mean (median, range) of 36.8 (22.8, 1.5-538.0) miles from the treating facility compared with 27.5 (19.4, 1.4-119.0) miles for patients treated before that date; this difference was not statistically significant ($P = .517$). When stratified by treatment regimen, patients receiving HYPORT lived farther from the treating facility than those receiving conventionally fractionated postprostatectomy radiation therapy (COPORT), with mean (median) travel distances of 43.2 (22.6) and 19.1 (17.3) miles, respectively ($P = .04$). However, this association did not remain significant after adjustment for treatment facility or after exclusion of patients residing outside the state, suggesting that the unadjusted finding was influenced by a small number of out-of-state patients. The geographic distribution of patient residences by county, stratified by treatment regimen (HYPORT vs COPORT), is shown in **Figure 1**.

Table 1. continued

	BEFORE MARCH 2024 (N = 37)	MARCH 2024 AND AFTER (N = 49)	*P* VALUE
Treatment facility			
Main	30 (81%)	33 (67%)	
Satellite	7 (19%)	16 (33%)	

All percentages are column percentages. P values are omitted for variables with insufficient counts in one or more categories to permit valid statistical comparison.

[a]*Welch 2-sample t test P value.*

[b]*Fisher exact test P value.*

[c]χ^2 *test P value.*

[d]*Mann-Whitney U test P value.*

ISUP, International Society of Urological Pathology; PSA, prostate-specific antigen; RT, radiation therapy.

Discussion

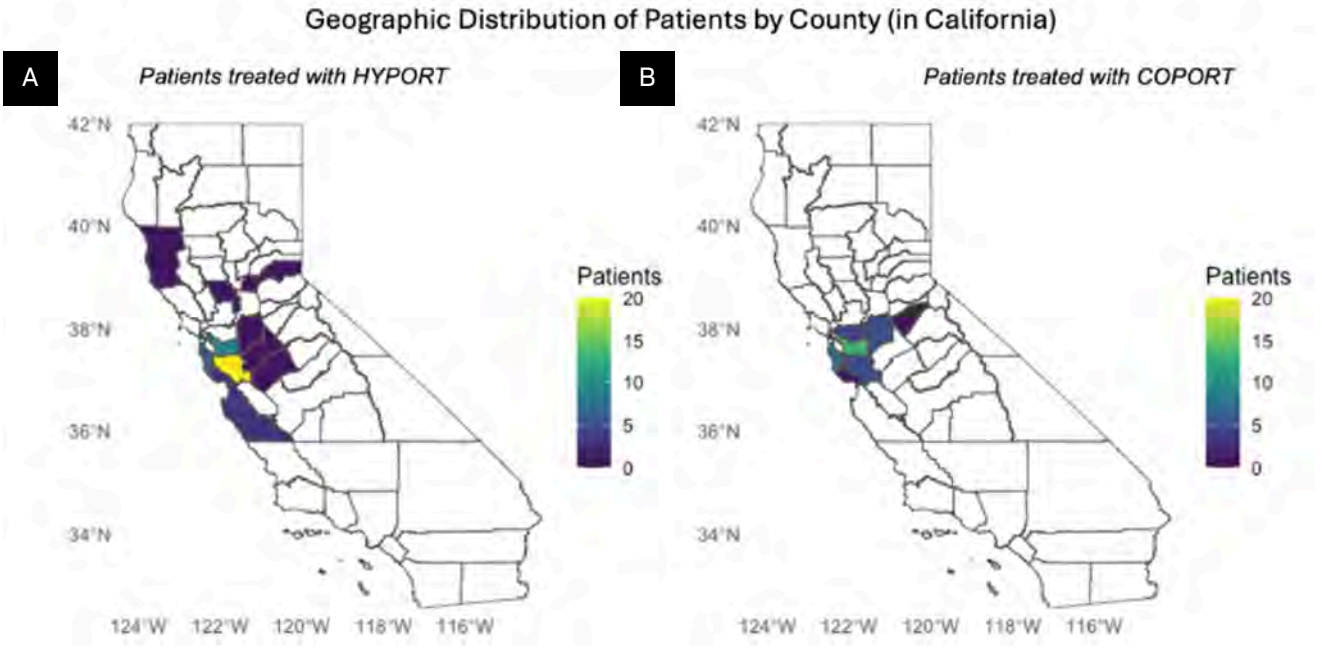
In this study, we examined changes in clinical practice for PPRT following the publication of NRG-GU003, focusing on treatment patterns, regimen selection, and geographic access. Of note, this study included patients who received either adjuvant or salvage RT, mirroring the patient cohort of NRG-GU003 and capturing a larger breadth of PPRT regimens. We observed a clear shift in practice beginning in March 2024, with increased adoption of HYPORT on both unadjusted and multivariable analyses. Importantly, this association remained significant and similar in magnitude after adjustment for treating physician, suggesting that the observed increase in HYPORT use was not solely attributable to differences in provider practice patterns.

While increased use of HYPORT after publication of NRG-GU003 may be expected, our analysis characterized early real-world implementation of HYPORT across a multisite radiation oncology network and evaluated whether this practice change was associated with differences in treatment delivery patterns and geographic reach. These findings may help contextualize how shorter-course regimens are incorporated into routine practice and whether they may reduce access-related barriers for patients who live farther from treatment facilities.

While not statistically significant, the numerical increase in patients treated with PPRT among this patient cohort contrasts with prior reports of decreasing use of PPRT (within 6 mo of surgery) from 2005 to 2011 for patients with adverse pathologic features, despite evidence from the SWOG Cancer Research Network and European Organisation for Research and Treatment of Cancer (EORTC) trials supporting improvements in relapse-free survival (RFS) and biochemical RFS with adjuvant RT.[13-17] Similarly, Hoffman and colleagues demonstrated a significant association between later year of diagnosis and decrease in recommendations for PPRT in a SEER analysis of patients who underwent prostatectomy in 2000 to 2007.[16] When year of diagnosis was analyzed as a dichotomized variable in the multivariable model, there was no difference in RT recommendations between the time periods before and after the SWOG and EORTC trials.

There are no prior reports in the post-prostatectomy literature that empirically link adoption of hypofractionated PPRT with the geographic reach of care. In our study, patients treated with HYPORT traveled a significantly greater distance for treatment than those treated with COPORT; however, this difference was not statistically significant after adjustment for treatment facility or in sensitivity analyses excluding out-of-state patients. This attenuation likely reflects the strong relationship between treatment facility and measured travel distance, as well as the influence of a small number of long-distance out-of-state patients in a modest cohort. Nevertheless, the logistical benefits of hypofractionation, including smaller time commitment, lower costs related to copayments, and fewer missed days from work, may lessen the obstacles

Figure 1. Geographic distribution of residences (California only) for patients who were treated with (A) hypofractionated postprostatectomy radiation therapy (HYPORT) vs (B) conventionally fractionated radiation therapy (COPORT). County shading represents the number of patients residing in each county, with dark purple indicating fewer patients and yellow indicating higher patient counts, as shown in the accompanying color bars.



many patients face when undergoing and coordinating RT. As a more convenient treatment schedule with fewer fractions may also alleviate the travel burden for patients, they may be more willing to seek care at facilities farther from home. Further prospective evaluation is warranted to determine whether HYPORT may mitigate travel-related barriers to PPRT, particularly for patients who live farther from treatment facilities.

This study carries several limitations. First, this was a retrospective analysis of patients treated at a single institution, limiting the generalizability of its findings. However, data were collected across 4 treatment facilities, which may lead to a more diverse patient population than that of a single-site institution. The total cohort size was limited, which reduced statistical power for subgroup analyses and for detecting differences in treated case volume and travel distance before vs after publication of NRG-GU003. The study also yielded wide confidence intervals in multivariable analyses; therefore, while the direction of the HYPORT adoption effect appeared robust, the precise magnitude of this association remains uncertain. Additionally, this study included only patients who received PPRT and did not include all patients who underwent radical prostatectomy or all patients referred for consideration of PPRT. Therefore, we were unable to evaluate overall PPRT utilization among all potentially eligible patients, and changes in the number of treated patients should be interpreted as changes in treated PPRT case volume within our radiation oncology cohort rather than population-level utilization. This study did not measure other variables, which may also have influenced the number of patients initiating HYPORT/PPRT, such as selection bias, evolving referral patterns, institutional growth, satellite expansion, centralization of care, and broader trends toward hypofractionation beyond NRG-GU003. The collection of additional data, such as patient-reported outcomes, socioeconomic status, and quality of life measures, would render a more comprehensive understanding of the potential impact of the establishment of hypofractionation on access to care.

Importantly, although our findings suggest that hypofractionation may help mitigate travel-related barriers, this study did not evaluate the full range of clinical, physician, and patient-level factors that inform fractionation selection. Long-term toxicity, disease control, baseline urinary function, comorbidities, and patient preference should also be considered. For example, one study of 161 consecutive patients treated with salvage hypofractionated PPRT, with a median follow-up of 13.5 years, reported late grade 3 to 5 toxicities in 44 patients (27.3%). Therefore, geographic access should be considered as one of several factors, rather than the sole determinant, when selecting a PPRT regimen.

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Conclusion

This multisite study demonstrated a significant shift in clinical practice, with a greater proportion of hypofractionated regimens delivered after the publication of NRG-GU003 in March 2024. In addition, patients treated after March 2024 traveled numerically greater distances for treatment, warranting further study of whether shorter treatment courses may reduce logistical barriers. Multi-institutional studies with larger cohorts are needed to clarify the impact of hypofractionation on access to PPRT.

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Stage 1A NLPHL Complete Response to 4 Gy VLDRT

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Abstract

Nodular lymphocyte-predominant Hodgkin lymphoma (NLPHL) is a rare, indolent subtype of Hodgkin lymphoma commonly treated with involved-site radiation therapy to 30 Gy for early-stage disease. Given its biologic overlap with indolent B-cell non-Hodgkin lymphoma, interest has emerged in radiation dose de-escalation to reduce long-term toxicity. We present the case of an adult man with stage 1A NLPHL involving right cervical lymph nodes treated with very low-dose radiation therapy (VLDRT) consisting of 4 Gy in 2 fractions following shared decision-making. Treatment was well tolerated without acute toxicity, and PET/CT at 3 months demonstrated a complete metabolic response. This case supports VLDRT as a potential low-toxicity option in selected patients while emphasizing the need for prolonged surveillance and prospective investigation regarding the durability of remission.

Keywords: nodular lymphocyte-predominant Hodgkin lymphoma, radiation therapy, low-dose radiation, lymphoma, survivorship

Case Summary

A 27-year-old man with no significant medical history presented with a right submandibular mass. He was otherwise asymptomatic, without fevers, night sweats, unintentional weight loss, or additional symptoms. CT imaging demonstrated a 1.5 × 1.4 cm enlarged right level 2 cervical lymph node. Initial fine-needle aspiration (FNA) was negative, and the lymphadenopathy regressed spontaneously. 22 months later, the patient returned with recurrent cervical lymphadenopathy without constitutional symptoms. Repeat FNA and core biopsy were nondiagnostic, prompting excisional biopsy, which demonstrated nodular lymphocyte-predominant Hodgkin lymphoma (NLPHL). PET/CT demonstrated hypermetabolic right cervical level 2 and 4 lymph nodes without distant disease, consistent with stage 1A NLPHL according to the Ann Arbor staging system for lymphoma. Standard involved-site radiation therapy (ISRT) to 30 Gy was recommended; however, after shared decision-making prioritizing toxicity reduction, the patient elected treatment with very low-dose radiation therapy (VLDRT) using 4 Gy in 2 fractions.

Imaging Findings

Initial contrast-enhanced CT imaging demonstrated an enlarged, right, level 2 cervical lymph node. Upon re-presentation, PET/CT demonstrated hypermetabolic right cervical level 2 and level 4 lymph nodes without distant disease, consistent

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Figure 1. Treatment planning images illustrating the pretreatment PET/CT demonstrating the extent of disease (A), with corresponding axial (B) and sagittal (C) views of the involved-site radiation therapy plan.

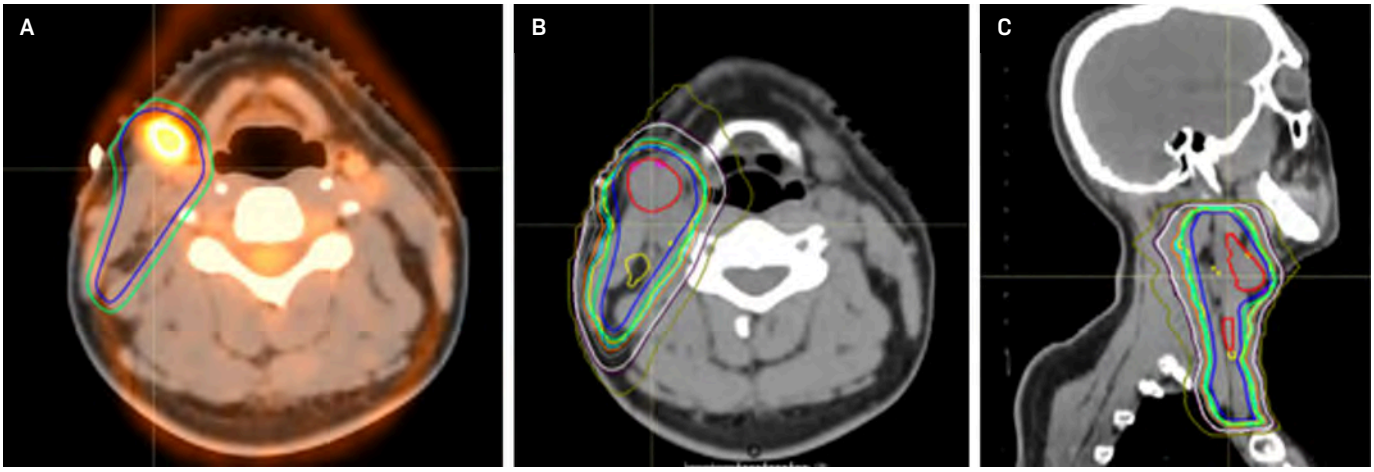
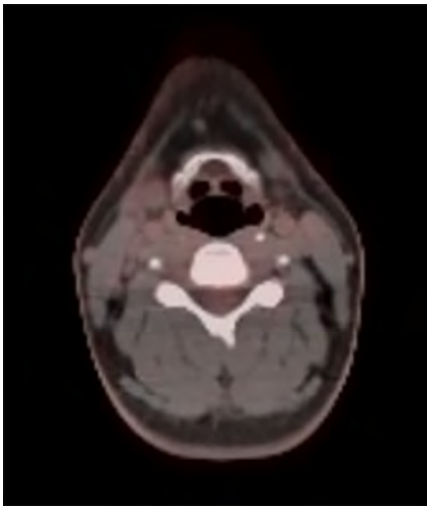


Figure 2. PET/CT 3 months following treatment demonstrating complete response.



with localized stage 1A NLPHL. **Figure 1** demonstrates pretreatment PET/CT imaging showing metabolically active cervical lymphadenopathy and corresponding axial and sagittal ISRT treatment-planning images encompassing the involved nodal regions. No bulky or extranodal disease was identified. For treatment planning, an ISRT approach was taken. The grossly involved nodes (gross tumor volume) were expanded with a margin to account for subclinical disease, resulting in a clinical target volume (CTV) that encompassed the involved and adjacent/intervening nodal basins (i.e., in this case, the CTV consisted of the involved right cervical lymph node stations, levels 2 and 4, as well as the intervening lymph node station, level 3). A 3-mm margin upon the CTV was added to make the planning target volume, deemed adequate given mask immobilization and plan for daily image guidance. Intensity-modulated radiation therapy was delivered to 4 Gy in 2 fractions, with care given to minimize dose to thyroid, carotids, salivary glands, and oral cavity. Following completion of VLDRT (4 Gy in 2 fractions), repeat PET/CT obtained 3 months later demonstrated complete metabolic response with resolution of previously identified hypermetabolic cervical lymphadenopathy (**Figure 2**), consistent with remission.

Diagnosis

Stage 1A NLPHL involving right cervical level 2 and level 4 lymph nodes. Differential considerations included reactive lymphadenopathy, classical Hodgkin lymphoma (cHL), and indolent B-cell non-Hodgkin lymphoma (NHL) prior to excisional biopsy confirmation.

Discussion

NLPHL is a rare subtype of Hodgkin lymphoma accounting for approximately 5% of Hodgkin lymphoma cases and most commonly affecting young adult men.[1] Unlike cHL, NLPHL is characterized by CD20-positive lymphocyte-predominant ("popcorn") cells lacking CD15 and CD30 expression.[2] Clinically, NLPHL behaves similarly to indolent B-cell NHL, with most patients presenting with localized peripheral lymphadenopathy and excellent long-term survival despite the risk of late relapse or transformation.[3-5]

Historically, early stage Hodgkin lymphoma was treated with extended-field radiation therapy, later replaced by involved-field radiation therapy and subsequently involved-site radiation therapy (ISRT) to reduce toxicity while maintaining disease control.[6,7] Current guidelines recommend definitive ISRT to 30 Gy in 15 fractions for stage 1A NLPHL without clinical risk factors.[8] When planning ISRT for stage 1 NLPHL, given that radiation is the primary treatment and no systemic therapy is given, the margins added to gross nodes should be accordingly generous to account for microscopic disease or subclinical spread,and as was done in this case, the involved and adjacent/intervening lymph node basins treated.[7] Long-term progression-free survival with standard-dose radiation therapy approaches 85% to 92% at 8 to 10 years.[1] Although effective, standard-dose radiation therapy exposes young patients to potential late toxicities,

including cardiovascular disease and secondary malignancies.

Interest in treatment de-escalation has emerged given the radiosensitivity of indolent lymphomas. The Follicular Radiotherapy Trial, a randomized phase 3 study comparing 24 Gy with 4 Gy in indolent NHL, demonstrated meaningful responses even at very low doses.[9] Additionally, a small 2009 series evaluating 4 Gy in 2 fractions for NLPHL demonstrated an overall response rate of 89% and complete response rate of 67%, although local relapse occurred in most patients during follow-up.[10] These findings suggest VLDRT may provide excellent initial disease control, but the durability of long-term remission remains uncertain. Importantly, salvage therapy remained effective in relapsed patients.[10]

In the present case, a 27-year-old man with stage 1A NLPHL achieved complete metabolic response following VLDRT consisting of 4 Gy in 2 fractions. The patient prioritized minimizing treatment burden and long-term toxicity during shared decision-making. An adaptive approach was employed in which additional radiation therapy would be considered depending on the interval PET response. Treatment was well tolerated without acute toxicity, and follow-up PET/CT at 3 months demonstrated complete remission.

Radiation dose minimization carries important survivorship implications in young patients with Hodgkin lymphoma. Analyses from the Childhood Cancer Survivor Study demonstrated increased long-term risks of cardiovascular disease and secondary malignant neoplasms following radiation exposure.[11,12] Survivors treated with supradiaphragmatic radiation doses of 30 Gy or greater experience significantly elevated mortality and cardiovascular risk persisting decades after therapy.[12,13] Radiation-associated secondary malignancies, including breast, lung, and gastrointestinal cancers, also increase over time.[12] Contemporary risk-adapted strategies using smaller treatment volumes and lower doses have reduced rates of severe chronic health conditions among survivors.[14-17]

This case suggests VLDRT may represent a reasonable treatment consideration in carefully selected patients with localized NLPHL prioritizing toxicity reduction. However, caution remains warranted given limited prospective evidence and the recognized risk of late relapse in NLPHL.[5] Longer follow-up and prospective studies are needed to define the safety, efficacy, and durability of VLDRT strategies in this population.

Conclusion

Nodular lymphocyte-predominant Hodgkin lymphoma may demonstrate substantial radiosensitivity to very low-dose radiation therapy. This case demonstrates complete metabolic response following treatment with 4 Gy in 2 fractions in a young patient with stage 1A disease. Beyond reducing acute treatment burden, dose reduction may lessen long-term risks of cardiovascular disease and secondary malignancy in carefully selected patients. However, durability of remission following VLDRT remains uncertain, and larger prospective studies with prolonged follow-up are required before routine adoption of this strategy.

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Augmented Reality Can Improve Real-World Brachytherapy

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Cira is a PGY-3 radiation oncology resident at MD Anderson Cancer Center working at the intersection of AI, augmented reality, and survivorship. Her projects include AI simulations for patient communication, survivorship care coordination tools, and AR for brachytherapy, guided by her belief that high-quality processes should exist in all aspects of patient care.

Brachytherapy is among the most procedurally demanding skills a radiation oncology resident can develop. Unlike external beam radiation therapy, where planning and delivery are largely separated in time, brachytherapy demands that the physician think spatially, act decisively, and coordinate a complex team in real time. The learning curve is steep, and the consequences of technical error are immediate.

With case volumes varying considerably across institutions, residents and educators are increasingly looking for new tools that can support the development of procedural expertise in brachytherapy. For these reasons, our specialty stands to benefit meaningfully from augmented reality (AR).

AR refers to the overlay of digital content, such as images, annotations, or 3D renderings, onto a user's real-world field of view through a wearable headset. Unlike virtual reality, which replaces the physical environment, AR keeps the operator present and adds information that would otherwise require looking away from the operative field.

Other procedural specialties have already begun to capitalize on this technology. Surgeons at UC Davis Health perform complex otolaryngologic and orthopedic operations using AR goggles that project 3D CT and MRI reconstructions into the operative field, allowing visualization of vascular and bony structures that would otherwise remain hidden.[1] Similarly, in interventional radiology, a growing body of literature suggests that AR-based tools improve procedural accuracy, shorten training duration, and increase trainee confidence, with intraprocedural guidance demonstrating accuracy within 5 mm in live patients.[2,3] These specialties share the challenge of having to guide instruments through anatomy that cannot always be seen, which is the case with brachytherapy.

Over the past 2 years, our institution has been exploring various ways to use AR to support brachytherapy training and performance. As the procedure requires physicians to consistently shift their attention among multiple modalities —US, diagnostic imaging, and other monitors— our first goal was to use the Apple Vision Pro headset to bring all of these screens into a single, customizable field of view. This allows the physician to work with fewer interruptions, review imaging, and reference patient details mid-procedure without breaking sterility. While using the headset, we were struck by how intuitive the gestures felt and how naturally a virtual screen could be placed within our fields of view.

In brachytherapy, procedural steps are numerous and team composition varies from case to case. We created the checklist as a web-based application that loads directly onto the headset and appears as a floating screen within the trainee's field of view. The trainee can move it in and out of sight with simple hand gestures while performing the procedure, allowing real-time progress tracking and timely communication with nursing and physics teams at the appropriate steps. A structured, visible checklist reduces

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cognitive load, frees mental bandwidth for skill acquisition rather than step recall, and provides an additional layer of safety and continuity across disciplines. Time-stamped tracking of each step also proved useful in highlighting inefficiencies worth examining in subsequent cases.

Translating 2D axial imaging into 3D spatial understanding under operative time pressure, as required with brachytherapy, is genuinely difficult. Using the AR headset to render DICOM data as interactive 3D models offers physicians a more direct way to engage with patient anatomy. The physician can assess applicator geometry, anticipate needle trajectory, and appreciate proximity to organs at risk in ways that scrolling through slices cannot replicate. The same platform places applicator schematics, manufacturer reference images, and other procedural materials within virtual reach, allowing the physician to consult them without stepping away from the operative field.

Perhaps the most consequential feature of AR-facilitated brachytherapy is real-time remote collaboration. The headset's outward-facing cameras allow a remote expert to see precisely what the operator sees and provide live guidance from a distance.[4] This capability could broaden access to subspecialty mentorship, supporting physicians as they expand or update brachytherapy programs. For trainees, it could provide additional opportunities to learn from experienced colleagues across institutions.

As with any emerging technology, AR is still maturing. The headset is heavier than we anticipated, and on days with multiple cases, the cumulative weight on the face would likely become a limitation. Lighter, more ergonomic iterations of the hardware will be important if AR is to be integrated into routine clinical practice. Beyond ergonomics, users with significant myopia require custom optical inserts, and connectivity within shielded brachytherapy suites can be inconsistent. The clinical evidence base in radiation oncology is also in its early stages. These challenges are being actively addressed, and successive iterations of the hardware and software continue to improve.

The trajectory is encouraging. As residents, we have an opportunity to engage with these tools early, contribute to their refinement, and help shape how they integrate into our specialty. By offering our perspectives now, we can ensure that AR technology continues to improve precision-driven procedures like brachytherapy and other areas of radiation oncology.

Note: This is the third in a series of Resident Voice columns addressing options for enhancing brachytherapy training in residency. See also Procedural Competency in Brachytherapy: Stepping Beyond Case Minimums and Closing the Global Brachytherapy Training Gap with Virtual Reality.

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