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Translation-based correction of rotational setup errors in radiotherapy: a simulation-based evaluation

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Technical Note

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Abstract

Introduction: Rotational setup errors remain a challenge in radiotherapy centers without six-degree-of-freedom (6DoF) couch correction systems. Small angular deviations may compromise target coverage and organ-at-risk sparing. Although image-guided radiotherapy (IGRT) has improved setup verification, many centers continue to rely on three-degree-of-freedom (3DoF) couches.

Innovation: This technical report evaluates an approximation in which small rotational setup deviations are represented as equivalent translational displacements using the vector cross-product formulation ($\Delta = \theta \times r$). Head-and-neck, breast, lung, pelvis, and thorax scenarios were modeled using an Elekta Infinity linear accelerator and Monaco TPS (version 6.1.4.0) with Monte Carlo dose calculation. Simulated rotational perturbations were assessed with and without translation-based correction using dose–volume histogram endpoints Dmean, D95, and V95.

Discussion: Translation-based correction improved D95 across all treatment sites. The largest improvement was observed in head-and-neck geometry (approximately 2%), while pelvic and thoracic scenarios demonstrated intermediate gains. Breast and lung cases showed measurable improvements. Dmean increased modestly, whereas V95 remained essentially unchanged, suggesting improved target coverage without compromising volumetric conformity.

Recommendations: Translation-based correction is not a substitute for 6DoF couch technology but may provide a low-cost mitigation strategy for centers limited to 3DoF correction capability. Future studies should include phantom validation and automated correction approaches.

Introduction

Rotational setup errors remain a persistent challenge in radiotherapy centres without access to six-degree-of-freedom (6DoF) couches. Even small angular deviations can compromise target coverage and organ-at-risk sparing. A 1° rotation at 10 cm from the isocentre, for example, results in a positional shift of ~1.75 mm, which can be clinically relevant in stereotactic and head-and-neck treatments where steep gradients and tight margins are common.[1–3] While 6DoF couches provide direct correction, their high cost limits adoption in many clinics, leaving most departments dependent on three-degree-of-freedom (3DoF) couches that correct only translations.[4]

Modern radiotherapy techniques such as intensity-modulated radiotherapy (IMRT), volumetric-modulated arc therapy (VMAT), stereotactic radiotherapy and stereotactic body radiotherapy rely on highly conformal dose distributions with steep dose gradients. As treatment precision increases, even minor rotational setup deviations may influence target coverage and normal tissue sparing. Although image-guided radiotherapy has improved setup verification, many treatment centres continue to operate without routine access to 6DoF correction systems because of financial and infrastructural limitations. Consequently, practical mitigation approaches for rotational errors remain clinically relevant, particularly in resource-limited radiotherapy environments. In current clinical workflows, uncorrected rotational errors may necessitate time-consuming manual patient repositioning, leading to increased treatment room occupancy and potential patient discomfort. By providing a translational approximation for small rotational deviations, such approaches may help reduce workflow interruptions while maintaining acceptable geometric accuracy in centres without immediate access to advanced rotational correction hardware.

Despite the availability of advanced couch correction systems, practical implementation remains challenging in many high-volume radiotherapy centres because of cost, workflow complexity and infrastructure requirements. As a result, translational compensation strategies for small rotational deviations may offer a clinically useful intermediate solution in situations where full rotational correction is unavailable. The present technical report therefore evaluates a simplified geometric approximation in which rotational setup deviations are represented as

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Table 1. Comparative dosimetric parameters with and without translation-based correction across representative treatment sites

Site	Dmean (%) (No Corr)	D95 (%) (No Corr)	V95 (%) (No Corr)	Dmean (%) (With Corr)	D95 (%) (With Corr)	V95 (%) (With Corr)	ΔDmean (%) (With - No)	ΔD95 (%) (With - No)	ΔV95 (%) (With - No)
Head and neck	87.38	53.94	50.31	87.73	55.98	50.3	0.35	2.04	−0.01
Breast	92.24	59.5	68.88	92.46	60.25	68.91	0.22	0.75	0.03
Lungs	93.49	61.84	74.07	93.75	62.66	74.09	0.26	0.82	0.02
Pelvis	92.96	60.26	72.38	93.33	61.82	72.39	0.37	1.56	0.01
Thorax	94.34	63.81	77.58	94.63	64.91	77.59	0.29	1.1	0.01

equivalent translational displacements, with the aim of assessing their potential dosimetric impact across representative treatment geometries.

Technical Approach

To address this gap, the present technical report evaluated a practical approximation in which small rotational setup errors were represented as equivalent linear displacements using the vector cross-product formulation. For a given point, the displacement (Δ) was estimated as:

$$\Delta = \theta \times r$$

where θ is the rotation vector (in radians), and r is the positional vector measured from the isocentre. The negative of this displacement was considered as the corrective translational shift. This first-order approximation is exact only at the selected reference point (e.g., isocentre or target centre of mass), but may reduce residual error for small angular deviations (typically $\lesssim$3–5°).[5]

Representative treatment scenarios based on common anatomical sites (head-and-neck, breast, lung, pelvis and thorax) were modelled using standard radiotherapy planning geometry. Five representative anatomical site scenarios were evaluated (one per treatment region). Clinical platform context included an Elekta Infinity linear accelerator with Monaco TPS (version 6.1.4.0), which employs a Monte Carlo dose calculation framework. Representative planning geometry was based on modern conformal inverse-planned treatment workflows (IMRT/VMAT-type scenarios). Simulated rotational perturbations were applied, and comparative dosimetric values with and without translation-based correction were assessed using standard DVH endpoints: Dmean, D95 and V95. Rotational perturbations conceptually represented pitch, roll and yaw deviations.

Statistical Analysis

As this technical report was intended as a feasibility demonstration using representative simulated treatment scenarios, results were evaluated descriptively as comparative percentage changes between corrected and uncorrected conditions. Inferential statistical testing was not performed because the study did not involve repeated patient-based datasets or population-level analysis.

Results

Results are summarised in Table 1 and illustrated in Figure 1, which compares D95 values with and without translation-based correction across representative treatment sites. Across all representative treatment sites, translation-based correction consistently improved D95. The largest improvement was observed in head-and-neck geometry (ΔD95 ≈ 2.0%). Pelvis and thorax scenarios showed intermediate gains (1.0–1.5%), while breast and lung cases demonstrated smaller but measurable improvements (0.7–0.8%).

Dmean increased modestly (0.2–0.4%), suggesting improved dose uniformity, whereas V95 remained essentially unchanged (<0.03% variation). These findings indicate that translation-based compensation may improve target coverage while preserving volumetric conformity under small rotational setup deviations.

Discussion

The present technical evaluation suggests that minor rotational setup errors may be partially compensated on 3DoF couches through equivalent translational correction. Although the approximation is not exact, simulations demonstrated consistent dosimetric improvements across multiple anatomical sites. The greatest benefit was observed in head-and-neck cases, with D95 improving by nearly 2%, reflecting the high sensitivity of these treatments to geometric deviations due to complex anatomy and steep dose gradients.[3,5] Pelvic and thoracic plans showed intermediate gains of 1.0–1.5%, while breast and lung plans demonstrated smaller improvements of 0.7–0.8%, consistent with their larger target volumes and more generous margins.

Even modest improvements in D95 may be clinically meaningful in high-precision radiotherapy, where small residual errors often require patient repositioning.[2,3] By reducing the dosimetric consequences of minor rotations, this approach offers a low-cost option to enhance treatment quality and reduce workflow disruptions in centres without access to 6DoF couches.

Alternative mitigation approaches include improved immobilisation, margin expansion and dedicated 6DoF couch correction systems.

Several limitations should be noted. The method is approximate and less accurate for rotations exceeding 5°. Validation was limited to simulations, and residual errors persist at points distant from the isocentre. Future studies should include phantom-based evaluation, integration into image-guided radiotherapy workflows and automated correction tools for clinical implementation.

Limitations

The translation-based correction used in this study represents a first-order geometric approximation in which small rotational setup errors are converted into equivalent linear displacements at a chosen reference point, such as the isocentre or target centre of mass. This approximation is most valid for small rotations

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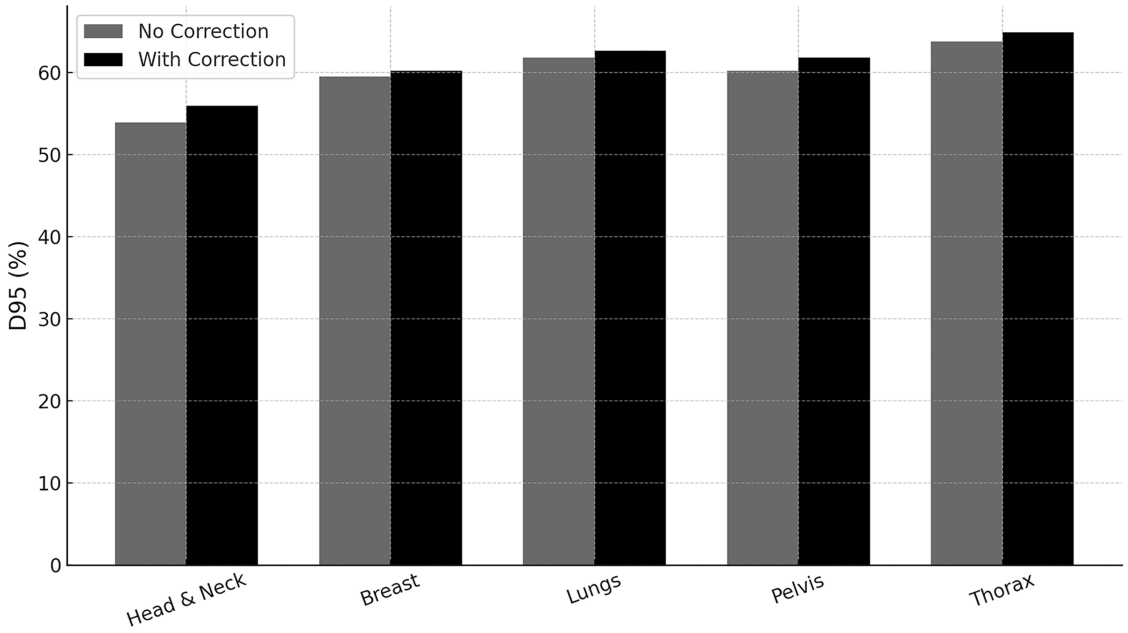


Figure 1. Comparison of D95 with and without translation-based correction across representative treatment sites.

(typically ≲3–5°), where higher-order nonlinear effects remain negligible. The correction is exact only at the selected reference point; residual errors increase with distance from this point and with increasing rotation magnitude. Consequently, this method does not replace 6DoF couch corrections, particularly for larger rotations or highly off-axis structures. Instead, it should be viewed as a pragmatic mitigation strategy that can reduce the dosimetric impact of minor rotational errors in centres limited to 3DoF couch corrections.

Conclusion

In summary, translation-based correction is not a substitute for 6DoF couch technology, but may provide a practical, low-cost mitigation strategy for centres limited to 3DoF correction capability.

Data availability and statement. All data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions. Subhrendu Ghosh: Conceptualisation, methodology, data analysis, manuscript preparation and final approval of the version to be published.

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Consent to participate. Not applicable.

Consent for publication. Not applicable.

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