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A Cone-Beam Computed Tomography (CBCT)-Derived Analysis of Inter-fraction Shifts and Correction Burden

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Abstract

Background

Stereotactic body radiotherapy (SBRT) requires sub-millimeter geometric precision because of the delivery of ablative radiation doses using highly conformal dose distributions and steep dose gradients. Inter-fraction translational and rotational setup deviations may compromise target coverage and increase radiation exposure to adjacent organs at risk. Daily cone-beam computed tomography (CBCT) with six-degrees-of-freedom (6DoF) couch correction enables comprehensive correction of positional errors; however, real-world data on the magnitude and distribution of these deviations remain limited, particularly from low- and middle-income settings.

Objective

The study aimed to characterize the magnitude and distribution of inter-fraction translational and rotational setup corrections in patients undergoing CBCT-guided SBRT with 6DoF couch correction, and to quantify the positional correction requirements across treatment fractions.

Methods

A retrospective observational study was conducted in the Department of Radiation Oncology, Swami Rama Himalayan University, Dehradun, India. Patients who underwent SBRT between January 2022 and December 2024 with daily CBCT guidance and 6DoF couch correction were included. Fraction-wise translational deviations along the lateral (X), longitudinal (Y), and vertical (Z) axes, and rotational deviations in pitch, roll, and yaw were extracted from the treatment delivery system. A three-dimensional rotational vector magnitude was calculated as a composite measure of rotational displacement. Descriptive statistical analysis was performed using mean ± standard deviation (SD) to summarize the absolute magnitudes of fraction-level translational and rotational setup corrections. No inferential statistical testing was performed.

Results

Fourteen patients contributed 48 evaluable CBCT-guided SBRT treatment fractions. The mean absolute translational corrections were 0.21 ± 0.18 cm laterally, 0.27 ± 0.22 cm longitudinally, and 0.24 ± 0.20 cm vertically, with the largest mean correction observed in the longitudinal direction. Mean absolute rotational corrections were 0.48 ± 0.36° for pitch, 0.44 ± 0.33° for roll, and 0.41 ± 0.31° for yaw. The mean three-dimensional rotational vector magnitude was 0.78 ± 0.42°.

Conclusion

Daily CBCT-guided 6DoF correction was associated with small inter-fraction translational and rotational setup corrections during SBRT. These findings provide institution-specific baseline data for evaluating immobilization and image-guidance workflows and may inform future patient-level assessment of residual setup uncertainty and planning target volume (PTV) margins.

Categories: Radiation Oncology
Keywords: cone-beam ct, image-guided radiotherapy, ptv margins, sbrt, setup uncertainty, six-degree-of-freedom couch, stereotactic body radiotherapy

Introduction

Stereotactic body radiation has emerged as a standard treatment modality for primary and metastatic malignancies because of its ability to deliver highly conformal doses in a restricted number of fractions with high conformality and steep dose gradients. The therapeutic advantage of stereotactic body radiotherapy (SBRT) depends on accurate target localization and reproducible patient positioning during the treatment course. Unlike conventional radiation, SBRT delivers a highly conformal dose in each fraction, making even

small setup deviations highly significant from both dosimetric and clinical perspectives [1,2].

Inter-fraction setup uncertainty remains an important source of geometric error in stereotactic radiation. Variations in patient positioning, immobilization reproducibility, respiratory motion, and anatomical changes between treatment fractions may result in translational and rotational deviations from the planned treatment position. Uncorrected translational errors can reduce target coverage and increase radiation exposure to adjacent organs at risk, while rotational errors may produce clinically relevant dosimetric inaccuracies, particularly for small targets and lesions located near critical structures. Consequently, precise image guidance before each treatment fraction has become an essential part of SBRT workflows [3-5].

Cone-beam computed tomography (CBCT)-based radiotherapy allows direct visualization of target volume and facilitates correction of inter-fraction positional errors immediately before radiation delivery [6]. The introduction of six-degrees-of-freedom (6DoF) couch systems has enabled simultaneous correction of three translational, i.e., lateral, longitudinal, and vertical, and three rotational, i.e., pitch, roll, and yaw, errors. Compared with conventional three-degrees-of-freedom systems, 6DoF correction provides more comprehensive alignment and reduces geometric uncertainty during SBRT treatment delivery [7-10].

Although CBCT-guided SBRT and 6DoF couch correction are increasingly used in routine clinical practice, published datasets describing fraction-level translational and rotational setup corrections remain heterogeneous across institutions and treatment sites. Studies from India and other regions have reported setup uncertainties and image-guidance performance in SBRT; however, institutional datasets incorporating simultaneous translational and rotational corrections using a 6DoF couch, together with a composite three-dimensional rotational vector magnitude, remain relatively limited. In this context, the present study provides institution-specific descriptive data from a tertiary-care center in India and characterizes the magnitude and distribution of fraction-level translational and rotational corrections during routine CBCT-guided SBRT.

Furthermore, rotational setup errors are increasingly recognized as clinically important. While translational corrections are routinely performed, the cumulative impact of rotational deviations may be underestimated when rotational uncertainties are analyzed independently [11,12]. The three-dimensional rotational vector magnitude provides a composite quantitative measure of overall rotational displacement and may provide an additional composite measure of the overall rotational displacement encountered during SBRT.

The present study was undertaken to analyse inter-fraction translational and rotational setup deviations in patients treated with CBCT-guided SBRT using a 6DoF couch correction system at a tertiary care center in India. The study aimed to characterize the magnitude and distribution of translational and rotational setup corrections in order to establish baseline institutional data on geometric reproducibility during routine SBRT delivery.

Materials And Methods

Aims and objective

The study aimed to characterize the magnitude and distribution of inter-fraction translational and rotational setup corrections in patients undergoing CBCT-guided SBRT with 6DoF couch correction, and to quantify the positional correction requirements across treatment fractions.

Study design and setting

This study was conducted in the Department of Radiation Oncology, Himalayan Institute of Medical Sciences, Dehradun, India, between January 2022 and December 2024.

The study evaluated inter-fraction translational and rotational setup corrections in patients treated with stereotactic body radiotherapy using daily cone-beam computed tomography and a six-degree-of-freedom couch correction system. Treatment records available during the study period were retrospectively reviewed. Institutional Ethics Committee approval was obtained before data collection.

Ethics statement

The study was conducted in accordance with the ethical standards of the institutional research committee and the Declaration of Helsinki. Institutional Ethics Committee approval was obtained from the Research Committee, Himalayan Institute of Medical Sciences, Dehradun, India, approval No. SRHU/HIMS/RC/2026/159. As this was a retrospective study involving review of existing treatment and image-guidance records without prospective intervention, the requirement for individual informed consent was waived by the Institutional Ethics Committee.

Study population

A consecutive, non-probability sampling method was used. All patients who underwent SBRT during the

study period and had the required image-guidance and couch-correction records available were screened for eligibility. A total of 14 patients were included in the study population (Table *1*). The anatomical sites treated with SBRT were classified according to the treatment site documented in the treatment records. Four patients were treated for lesions of the cervix uteri, three for lung lesions, four for spinal lesions, and three for femoral lesions. Individual treatment fractions were included when the required CBCT-derived translational and rotational setup-correction parameters were available. Selection of treatment fractions was based on data availability and was not based on the magnitude or direction of the observed setup correction.

Characteristic	n (%)
Cervical uteri	4 (28.6)
Lung	3 (21.4)
Spine	4 (28.6)
Femur	3 (21.4)
Total patients	14 (100)

TABLE 1: Patient cohort (n=14)

Four patients were treated for lesions of the cervix uteri, three for lung lesions, four for spinal lesions, and three for femoral lesions.

Sample size

No a priori sample-size calculation was performed. As this was a retrospective observational study, the sample consisted of all eligible patients available during the predefined study period.

Inclusion and exclusion criteria

Inclusion Criteria: 1. Patients who received SBRT for primary, recurrent, or metastatic malignant lesions; 2. Patients who underwent CBCT-based image guidance before every treatment fraction; 3. Patients who underwent image-guided positional correction performed using a 6DoF couch system; and 4. Patients for whom complete fraction-wise CBCT-derived translational and rotational setup-correction data were available for the treatment fractions included in the analysis.

For translational analysis, treatment fractions were required to contain evaluable lateral, longitudinal, and vertical couch-correction values. For rotational analysis, evaluable pitch, roll, and yaw correction values were required.

Exclusion Criteria: 1. Patients who received conventional radiotherapy; 2. Patients who did not complete the planned SBRT course; and 3. Treatment fractions for which the required CBCT or couch-correction parameters were unavailable or incomplete.

Stereotactic body radiotherapy site-specific treatment protocols

Stereotactic body radiotherapy was delivered according to institutional site-specific treatment protocols. The cohort included lesions involving the cervix uteri, lung, spine, and femur. The number of fractions was determined according to the anatomical treatment site, clinical indication, target characteristics, proximity to organs at risk, and the treating radiation oncologist's assessment.

For cervix uteri and pelvic targets, reproducible pelvic positioning with rigid immobilization was used, with attention to alignment of the pelvic anatomy and target region during pre-treatment CBCT verification.

For lung SBRT, patients were positioned using the institutional SBRT immobilization technique, with attention to reproducible thoracic positioning and target localization during pre-treatment CBCT verification.

For spinal SBRT, accurate alignment of the involved vertebral anatomy and target region was emphasized because of the close relationship between the target and adjacent critical structures.

For femoral SBRT, reproducible limb positioning and alignment of the involved femur and adjacent bony anatomy were emphasized.

In all treatment sites, volumetric CBCT verification was performed before treatment delivery, and detected setup discrepancies were corrected using the 6DoF couch before irradiation.

Immobilization, CBCT acquisition, and image matching

Patients were positioned using rigid, site-appropriate immobilization according to the institutional SBRT protocol. Before each treatment fraction, volumetric CBCT was acquired with the patient in the treatment position and registered with the corresponding planning CT dataset.

Image registration was performed according to the institutional image-guided radiotherapy workflow using anatomical structures relevant to the treatment site. For cervix uteri and pelvic targets, registration focused on the target region and surrounding pelvic anatomy. For lung lesions, registration focused on the thoracic anatomy and target region. For spinal lesions, registration emphasized the involved vertebral anatomy and target region. For femoral lesions, registration emphasized the involved femur and adjacent bony anatomy.

The CBCT-to-planning-CT registration was reviewed before treatment delivery, and positional adjustments were made when required. Following satisfactory registration, positional discrepancies were corrected using the 6DoF treatment couch. Corrections were applied in three translational directions-lateral, longitudinal, and vertical-and three rotational directions-pitch, roll, and yaw.

The recorded values represented the couch corrections required following CBCT registration and were used as measures of pre-treatment inter-fraction setup deviation. They do not represent residual positioning error after correction.

Treatment planning and data extraction

Treatment and image-guidance records were retrospectively accessed through departmental data records. The corresponding planning CT datasets and radiotherapy treatment-planning information were reviewed using the Eclipse Treatment Planning System (Varian Medical Systems, Palo Alto, USA).

Fraction-wise couch-correction parameters were retrospectively extracted from the treatment delivery and image-guidance records. For each couch parameter, the treatment system recorded the image position, treatment position, and corresponding positional difference. The system-generated difference was used as the measure of the positional correction required following CBCT registration.

As this was a retrospective study, detailed demographic and treatment characteristics beyond treatment site were not consistently available across all retrospectively reviewed records and were therefore not included as study variables in the present analysis.

Measurement of translational and rotational setup shifts

Translational setup deviations were recorded along three orthogonal axes: lateral (X), longitudinal (Y), and vertical (Z). Translational correction values were expressed in centimeters.

The sign of each translational and rotational correction followed the coordinate convention of the treatment couch and image-guidance system, with positive and negative values representing opposite directions along each axis. For the primary descriptive analysis, the absolute magnitude of each correction was used rather than the signed value. Therefore, the reported mean ± standard deviation represents the magnitude of setup correction and does not indicate the predominant direction of displacement.

Rotational setup deviations were recorded as pitch, roll, and yaw. They were expressed in degrees. These six parameters represented the correction required to align the CBCT-derived treatment position with the planned position before treatment delivery.

For rotational measurements crossing the 0°/360° boundary, the system-reported correction difference was used rather than direct arithmetic subtraction of the absolute angular coordinates. This approach avoided artificially large rotational differences resulting from angular wrap-around.

No separate numerical threshold for repeat CBCT or rejection of a couch correction was retrospectively defined for this study. Setup corrections were reviewed as part of the routine institutional image-guidance workflow before treatment delivery.

Three-dimensional rotational vector magnitude

For treatment fractions with complete rotational measurements, the three-dimensional rotational vector magnitude was calculated using the Euclidean norm of the pitch, roll, and yaw corrections,

$$R_3D = \sqrt{\text{pitch}^2 + \text{roll}^2 + \text{yaw}^2}$$

where pitch, roll, and yaw were expressed in degrees. The resulting value was used as a composite descriptive measure of the overall rotational correction required during an individual treatment fraction.

Outcome measures

The primary outcome was the magnitude and distribution of inter-fraction translational and rotational setup corrections during CBCT-guided SBRT. No threshold-based definition of clinically significant correction or correction burden was prespecified in this retrospective analysis. Translational deviations were evaluated independently in the lateral, longitudinal, and vertical directions, while rotational deviations were evaluated independently as pitch, roll, and yaw.

The three-dimensional rotational vector magnitude was additionally evaluated as a composite measure of overall rotational displacement.

Statistical analysis

Descriptive statistics were used to summarize patient characteristics and fraction-level translational and rotational setup corrections. Continuous variables were expressed as mean ± standard deviation (SD). Absolute translational correction magnitudes were evaluated separately along the lateral (X), longitudinal (Y), and vertical (Z) axes. Absolute rotational correction magnitudes were evaluated for pitch, roll, and yaw. The three-dimensional rotational vector magnitude was calculated for each fraction with complete rotational data using the formula $R_3D = \sqrt{\text{pitch}^2 + \text{roll}^2 + \text{yaw}^2}$ and summarized using mean ± SD.

Multiple fractions from the same patient were retained for fraction-level descriptive analysis. No inferential statistical testing was performed. Median, interquartile range, and 95th percentile values were not calculated. Patient-level systematic error (Σ), random error (σ), and planning target volume (PTV) margins were not estimated.

Results

The patient-wise distribution of diagnoses, SBRT treatment sites, and the corresponding treatment fractions is presented in Table *2*.

Patient number	Diagnosis	SBRT treatment site recorded	Recorded fraction blocks
P01	Recurrent carcinoma cervix	Pelvis	5
P02	Carcinoma cervix	Cervix	4
P03	Carcinoma cervix	Pelvis / cervix	5
P04	Carcinoma lung	Lung	5
P05	Carcinoma lung	Lung	5
P06	Metastatic carcinoma stomach	Spine	4
P07	Metastatic carcinoma lung	Spine	4
P08	Metastatic carcinoma breast	Spine	5
P09	Metastatic carcinoma rectum	Lung	4
P10	Metastatic carcinoma breast	Spine	3
P11	Metastatic breast	Femur	5
P12	Metastatic carcinoma breast	Femur	3
P13	Metastatic carcinoma lung	Pelvis	5
P14	Metastatic soft tissue sarcoma	Right femur	5
Total	14 patients		62

TABLE 2: Site-wise distribution of evaluable SBRT treatment fractions and patient-wise fractionation according to anatomical treatment site and clinical characteristics

Different SBRT fractionation schedules were employed among patients based on individual disease characteristics, anatomical site, target volume, proximity to adjacent organs at risk, and patient-specific clinical factors, including anticipated treatment tolerance. Therefore, the number of fractions varied between patients according to the treating radiation oncologist's clinical assessment and individualized treatment requirements.

SBRT: stereotactic body radiotherapy

A total of 14 patients who underwent stereotactic body radiotherapy with daily CBCT using 6DoF couch corrections were included in the analysis, as summarized in the patient selection flowchart (Figure *1*). Forty-eight treatment fractions with complete translational and rotational correction data were evaluated, and the corresponding setup deviations were assessed descriptively.

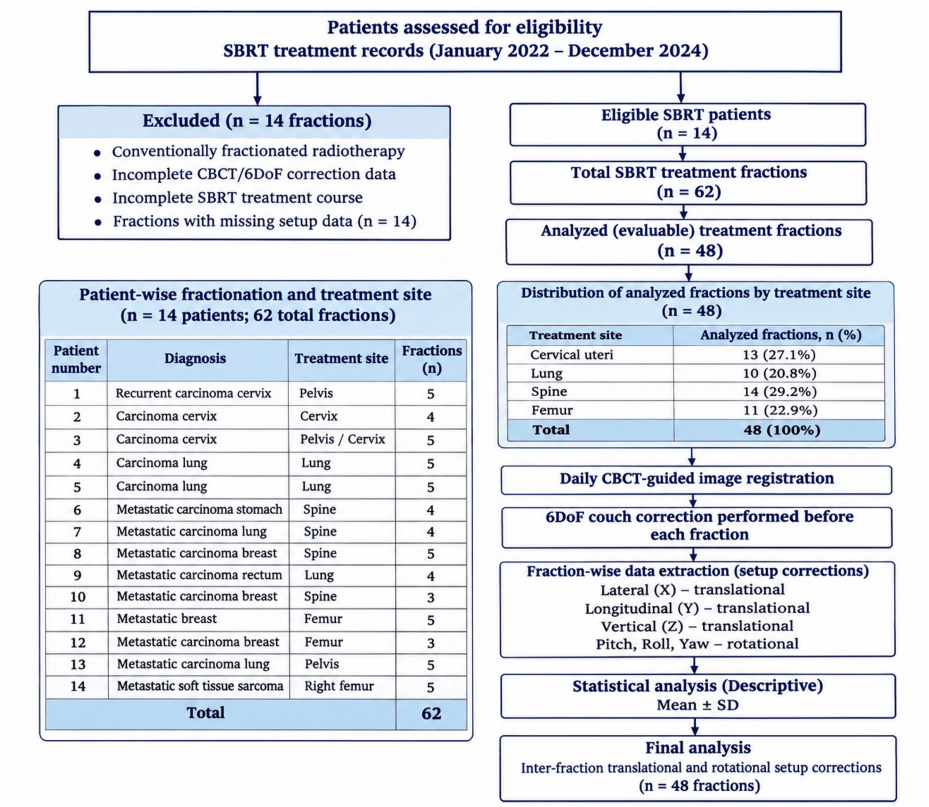


FIGURE 1: Flowchart of patient selection and analysis workflow.

The flowchart illustrates patient screening, eligibility assessment, inclusion, and fraction-level analysis.

Created using Microsoft PowerPoint (Microsoft Corp., Redmond, WA, USA).

CBCT: cone-beam computed tomography; SBRT: stereotactic body radiotherapy; 6DoF: six-degrees-of-freedom

Patient and treatment characteristics

The baseline characteristics of the study cohort are presented in Table 3. A total of 14 patients were included in the study cohort. All patients underwent daily CBCT image guidance with 6DoF couch-based positional correction and were treated using rigid, site-appropriate immobilization. A total of 48 treatment fractions with complete translational and rotational correction data were available for fraction-level analysis.

Characteristic	Value
Patients	14
Total CBCT-guided SBRT fractions analyzed	48
Daily cone-beam CT image guidance, n (%)	14 (100%)
Six-degree-of-freedom couch correction, n (%)	14 (100%)
Rigid immobilization devices, n (%)	14 100%)

TABLE 3: Patient and treatment characteristics (n = 14)

There were total 14 patients in the study population (n= 14). A total of 48 treatment fractions were available for fraction-level analysis.

Translational setup deviations

The descriptive statistics of translational setup corrections along the lateral (X), longitudinal (Y), and vertical (Z) axes are presented in Table 4. The mean absolute lateral correction was 0.21 ± 0.18 cm, the mean absolute longitudinal correction was 0.27 ± 0.22 cm, and the mean absolute vertical correction was 0.24 ± 0.20 cm. All mean translational corrections were within the sub-centimetric range. Among the three translational axes, the longitudinal direction demonstrated the largest mean correction. The standard deviations were of a similar order of magnitude to the corresponding means, indicating variability in fraction-level setup corrections.

Direction (axis)	n	Mean shift + SD (cm)
Lateral (X)	48	0.21 ± 0.18
Longitudinal (Y)	48	0.27 ± 0.22
Vertical (Z)	48	0.24 ± 0.20

TABLE 4: Descriptive statistics of translational setup corrections (n = 48 fractions)

Values are presented as mean ± standard deviation (SD). Values represent absolute translational correction magnitudes across 48 treatment fractions. X, lateral; Y, longitudinal; Z, vertical. No inferential statistical testing was performed.

Rotational setup deviations

The rotational setup corrections for pitch, roll, and yaw are summarized in Table 5. The mean absolute pitch correction was 0.48 ± 0.36°, the mean absolute roll correction was 0.44 ± 0.33°, and the mean absolute yaw correction was 0.41 ± 0.31°. Mean absolute rotational corrections were below 0.5° for all three axes. The standard deviations indicated variability in fraction-level rotational corrections. No inferential statistical testing was performed because the primary objective was to descriptively characterize inter-fraction setup corrections.

Rotational parameter	n	Mean absolute correction ± SD (°)
Pitch	48	0.48 ± 0.36
Roll	48	0.44 ± 0.33
Yaw	48	0.41 ± 0.31

TABLE 5: Descriptive statistics of rotational setup corrections (n = 48 fractions)

Values are presented as mean ± standard deviation (SD). Values represent absolute rotational correction magnitudes across 48 treatment fractions. No inferential statistical testing was performed.

Three-dimensional rotational vector magnitude

The three-dimensional (3D) rotational vector magnitude, representing the composite rotational displacement calculated from the pitch, roll, and yaw components, is presented in Table 6. The mean 3D rotational vector magnitude was 0.78 ± 0.42°. The standard deviation relative to the mean indicates meaningful variability in composite rotational displacement between treatment fractions.

Parameter	n	Mean ± SD (°)
3D rotational vector magnitude (°)	48	0.78 ± 0.42

TABLE 6: Descriptive statistics of three-dimensional rotational vector magnitude (n=48 fractions)

Values are presented as mean ± standard deviation (SD). The three-dimensional rotational vector magnitude was calculated as $\sqrt{(pitch^2 + roll^2 + yaw^2)}$ for each treatment fraction with complete rotational measurements. No inferential statistical testing was performed.

An overall summary of translational and rotational setup deviations for the

study cohort is presented in Table 7. Mean translational shifts ranged from 0.21 to 0.27 cm, while mean rotational deviations ranged from 0.41° to 0.48°. The 3D rotational vector magnitude averaged 0.78 ± 0.42°. Overall, the study demonstrated predominantly sub-centimetric mean translational corrections and mean rotational deviations below 0.5° per axis.

Parameter	n	Mean ± SD
Lateral (X) shift (cm)	48	0.21 ± 0.18
Longitudinal (Y) shift (cm)	48	0.27 ± 0.22
Vertical (Z) shift (cm)	48	0.24 ± 0.20
Pitch (°)	48	0.48 ± 0.36
Roll (°)	48	0.44 ± 0.33
Yaw (°)	48	0.41 ± 0.31
3D rotational vector magnitude (°)	48	0.78 ± 0.42

TABLE 7: Overall summary of setup deviations

Discussion

The present study evaluated inter-fraction translational and rotational setup corrections in patients undergoing stereotactic body radiotherapy (SBRT) using daily cone-beam computed tomography (CBCT)-guided six-degree-of-freedom (6DoF) couch correction. Across 48 evaluable treatment fractions, the observed mean translational corrections were within the sub-centimetric range, while mean rotational corrections were below 0.5° for each individual rotational axis. These findings describe the magnitude of pre-treatment positional corrections required during routine SBRT delivery and provide institution-specific baseline data for evaluating setup reproducibility and image-guidance workflows.

The mean translational setup deviations observed in the present study were 0.21 cm in the lateral direction, 0.27 cm in the longitudinal direction, and 0.24 cm in the vertical direction. These values indicate that inter-fraction positional corrections were small. The longitudinal direction demonstrated the highest mean correction and variability among the three translational axes, suggesting that superior-inferior positioning may represent an important component of inter-fraction setup uncertainty. Variations in patient positioning, relaxation within immobilization devices, respiratory motion, and anatomical changes between fractions may contribute to such deviations.

Purdie et al. [13] evaluated CBCT-guided lung stereotactic radiotherapy and demonstrated that volumetric tumor localization can identify positional discrepancies that may not be adequately represented by external positioning or bony-anatomy alignment alone. Their findings also demonstrated the value of repeat imaging for evaluating the stability of tumor position after initial correction. Sonke et al. [14] subsequently reported the use of four-dimensional CBCT guidance for frameless lung SBRT and showed that image-guided correction can substantially improve target localization, while residual localization and intra-fraction uncertainties remain relevant considerations. These observations are particularly important when interpreting the present study because the correction values analyzed here represent pre-treatment setup deviations rather than residual post-correction errors.

Our findings are also consistent with other reports evaluating image-guided setup accuracy in SBRT. Rossi et al. [15] demonstrated that post-correction validation imaging can identify residual tumor misalignment during lung SBRT and emphasized the importance of verification following positional correction. Similarly, Li et al. [16] demonstrated predominantly small setup deviations during image-guided lung SBRT, supporting the role of daily imaging in maintaining geometric precision. Garibaldi et al. [17] reported translational and rotational localization errors during CBCT-guided lung stereotactic radiotherapy and demonstrated the additional geometric benefit of six-dimensional correction. The magnitude of the translational corrections observed in the present study is broadly consistent with published SBRT data and provides institution-specific descriptive information regarding setup reproducibility with immobilization and volumetric image guidance.

The influence of immobilization technique should also be considered when interpreting setup corrections. Ueda et al. [18] evaluated initial setup errors associated with two immobilization devices used for lung SBRT and demonstrated that the immobilization approach can influence the magnitude and reproducibility of

initial patient setup. These findings support the concept that setup uncertainty reflects not only patient-related variation but also the reproducibility of the immobilization, indexing, and positioning system. Consequently, periodic evaluation of institutional immobilization performance may represent an important component of SBRT quality assurance.

Rotational setup deviations in the present study were also relatively small, with mean corrections of 0.48° for pitch, 0.44° for roll and 0.41° for yaw. These findings demonstrate that measurable rotational corrections were encountered during routine SBRT setup and could be addressed using the available 6DoF couch correction workflow. Chang et al. [19] demonstrated the feasibility and clinical relevance of six-dimensional image guidance for spinal SBRT, highlighting the importance of correcting rotational as well as translational discrepancies in high-precision treatment. This may be particularly relevant in SBRT, where steep dose gradients and relatively small treatment margins increase the potential dosimetric consequences of geometric misalignment.

The mean 3D rotational vector magnitude of 0.78° in the present study provided a composite descriptive measure of rotational correction across pitch, roll, and yaw. Although the individual rotational axes remain clinically important, assessment of the rotational components together provides an additional descriptive measure of the overall rotational correction observed during treatment.

The potential dosimetric consequences of rotational setup errors have been demonstrated in several investigations. Sasaki et al. [20] showed that translational and rotational setup errors can adversely influence dose distribution during spine SBRT. Cao et al. [21] similarly demonstrated the dosimetric relevance of rotational setup errors in liver SBRT. Rotational errors may be particularly relevant for elongated targets, spinal lesions, and targets located at a distance from the treatment isocenter because even a relatively small angular deviation may translate into a larger spatial displacement at the target periphery. Taken together, these findings support the assessment and correction of rotational as well as translational discrepancies during high-precision SBRT. However, the present study did not directly evaluate the dosimetric consequences of the observed corrections.

The study included repeated fraction-level observations from the same patients. Although these observations were appropriate for describing the distribution of setup corrections encountered during treatment delivery, they were not considered statistically independent for inferential analysis. The small cohort also precluded robust patient-level estimation of systematic and random setup errors.

Implications for future planning target volume (PTV) margin assessment

The present findings also have implications for planning target volume (PTV) margin selection. The generally small mean translational and rotational corrections suggest that rigid immobilization combined with daily CBCT-guided 6DoF correction can reduce geometric uncertainty immediately before treatment delivery. However, the correction values reported in this study represent pre-treatment setup deviations that were identified and corrected rather than residual post-correction errors. Therefore, these data should not be interpreted as direct evidence for reducing PTV margins.

This distinction between pre-treatment correction magnitude and residual geometric uncertainty is important for margin determination. Van Herk emphasized that radiotherapy margins should account for systematic and random geometric uncertainties rather than being derived simply from the average magnitude of setup displacement [22]. PTV margin selection should therefore ideally incorporate patient-level systematic error (Σ), random error (σ), residual post-correction uncertainty, target motion, image-registration uncertainty, and disease-site-specific considerations.

Sonke et al. incorporated residual localization uncertainty, baseline variation, and intrafraction positional stability when evaluating image-guided lung SBRT and associated margin requirements [14]. Bissonnette et al. [23] evaluated volumetric CBCT guidance with online couch adjustment and demonstrated the importance of systematic and random positioning uncertainties when assessing population setup margins. Cuijpers et al. [24] further analyzed components of variance contributing to setup errors during CBCT-guided stereotactic radiotherapy of lung tumors, emphasizing that multiple sources of geometric variation may contribute to the final uncertainty surrounding target localization. These studies reinforce that mean pre-treatment couch-correction values alone are insufficient for deriving a definitive numerical PTV margin.

Because systematic and random errors and residual post-correction deviations were not calculated in the present analysis, institution-specific numerical PTV margins cannot be recommended from the current data alone. Nevertheless, the observed correction pattern provides an important foundation for subsequent margin studies.

For clinical practice, the findings support maintaining adequate PTV margins unless formal margin validation has been performed using residual setup data. Any future attempt to reduce margins should therefore be accompanied by systematic evaluation of post-correction CBCT accuracy and calculation of Σ

and σ, preferably separately for different anatomical SBRT sites. Such an approach would allow margin reduction, where appropriate, to be based on institution-specific evidence rather than on mean pre-treatment corrections alone [7,14-16].

Clinical implications for SBRT workflow

The findings also have practical implications for the SBRT treatment workflow. First, daily CBCT should remain an integral component of SBRT delivery because even patients positioned using rigid immobilization required measurable translational and rotational corrections before treatment. Reliance on external setup or immobilization alone would therefore be insufficient for ensuring treatment-position accuracy.

Second, the longitudinal direction demonstrated the largest mean translational correction in the present study and should receive particular attention during image registration and verification. Careful assessment of superior-inferior alignment may be especially important for treatment sites influenced by respiratory motion or variability in longitudinal patient positioning.

Third, measurable pitch, roll, and yaw corrections were observed across treatment fractions, highlighting the presence of rotational components within inter-fraction setup variation. The availability of 6DoF couch correction provides a mechanism to correct these rotational components during the image-guided workflow; however, this study was not designed to compare 6DoF with 3DoF correction.

Fourth, correction data can be incorporated into institutional quality-assurance programs. Periodic review of site-specific setup corrections may help identify systematic positioning problems, evaluate the performance of immobilization techniques and determine whether modifications to simulation, indexing, patient preparation, or image-registration procedures are required. Establishing site-specific action thresholds for unusually large corrections may also be useful; such cases could prompt repeat image registration, repositioning, or repeat CBCT before treatment rather than automatic acceptance of a large couch shift.

The interval between image acquisition, positional correction, and treatment delivery may also influence geometric accuracy. Purdie et al. demonstrated that tumor position can change between initial localization and subsequent verification imaging, highlighting that an accurate initial correction does not necessarily guarantee positional stability throughout the treatment process [13]. Bissonnette et al. evaluated repeat volumetric imaging following online couch adjustment [23], while Rossi et al. specifically assessed the role of post-correction validation scans in identifying residual tumor misalignment during lung SBRT [15]. These observations support an efficient image-to-treatment workflow and suggest that repeat verification may be particularly valuable when large corrections are required, treatment delivery is prolonged, or target motion is a concern.

Finally, as institutional experience and patient numbers increase, treatment-site-specific analysis may permit further refinement of the workflow. Sites demonstrating consistently small residual uncertainties after correction may eventually be considered for carefully validated margin optimization, whereas sites with greater residual variability may require more stringent immobilization, repeated verification imaging, or larger margins. Such decisions should be based on formal site-specific analysis rather than on cohort-level mean correction values alone.

An important clinical implication of the present study is therefore not simply that setup corrections were generally small, but that daily CBCT and 6DoF correction provide a mechanism for identifying and correcting inter-fraction positional variation before delivery of an ablative radiation dose. The results provide baseline institutional data describing the role of daily CBCT and 6DoF correction in identifying and correcting inter-fraction positional variation before treatment delivery, and may inform future quality assurance, site-specific protocol refinement, and formal PTV-margin validation.

The present study has several limitations. First, it was a small, heterogeneous, single-center retrospective study comprising 14 patients and 48 evaluable treatment fractions across different SBRT treatment sites. Therefore, the findings should be interpreted as institution-specific descriptive observations and may not be generalizable to other patient populations, treatment sites, or image-guidance workflows. Second, the study quantified pre-treatment CBCT-derived translational and rotational couch corrections rather than residual geometric errors after correction. The magnitude of a couch correction should therefore not be interpreted as equivalent to the residual setup error remaining during treatment. Third, the study did not evaluate the dosimetric consequences of the observed setup corrections, nor did it estimate patient-level systematic error (Σ), random error (σ), or validate institution-specific PTV margins. Accordingly, these findings should not be used independently to reduce or modify currently applied PTV margins. Prospective studies incorporating residual post-correction uncertainty, patient-level systematic and random errors, and dosimetric assessment are required before the findings can inform margin optimization.

Overall, daily CBCT-guided 6DoF correction demonstrated generally small pre-treatment translational and rotational setup corrections during SBRT. The longitudinal axis showed the greatest mean translational

correction magnitude, while the 3D rotational vector magnitude remained relatively small. These findings provide institution-specific descriptive data on the magnitude of setup corrections encountered during routine image-guided SBRT and may inform future quality-assurance and site-specific workflow assessment. They do not, however, establish residual post-correction accuracy, dosimetric or clinical significance, superiority of 6DoF over 3DoF correction, or appropriate PTV margins. Further patient-level systematic and random error analysis, residual-error assessment, and formal site-specific PTV-margin validation are warranted.

Conclusions

Daily cone-beam computed tomography (CBCT)-guided six-degree-of-freedom (6DoF) couch correction was associated with small inter-fraction translational and rotational setup corrections during stereotactic body radiotherapy (SBRT). The mean translational corrections were 0.21 ± 0.18 cm laterally, 0.27 ± 0.22 cm longitudinally, and 0.24 ± 0.20 cm vertically, while mean rotational corrections were 0.48 ± 0.36° for pitch, 0.44 ± 0.33° for roll, and 0.41 ± 0.31° for yaw. The mean three-dimensional rotational vector magnitude was 0.78 ± 0.42°. These findings provide institution-specific descriptive data regarding fraction-level setup corrections during routine CBCT-guided SBRT and may support quality assurance and workflow optimization. Further studies incorporating patient-level systematic and random error estimation, residual post-correction assessment, and dosimetric analysis are warranted to evaluate the implications of these uncertainties for PTV margin selection.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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