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Usefulness of a head rotational correction device utilizing optical surface imaging in surface-guided radiation therapy

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► ***Original article***

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ABSTRACT

Background: Precise patient positioning is essential to effective head radiotherapy. However, helical tomotherapy lacks six-degree-of-freedom (6DoF) correction, limiting its ability to adjust for pitch and yaw errors. Optical surface imaging (OSI) enables non-invasive, real-time monitoring of patient position but exhibits limitations. ***Materials and Methods:*** A rotational correction device (RCD) was developed consisting of acrylic and steel adjustment components integrated into a carbon-fiber head-fixation baseplate. The phantom head is immobilized using a thermoplastic mask and positioned on the RCD. The setup accuracy and time were compared between the megavoltage computed tomography (MVCT)-based image-guided correction and OSI-assisted correction using an RCD. Ten trials were conducted for each system to measure the setup errors (translational and rotational magnitudes) and the total setup time. Treatment plans with a yaw error of 3° assessed the dosimetric impact on three spherical clinical target volumes (CTVs) and compared them with plans corrected using the RCD. ***Results:*** The RCD system significantly reduced setup errors (0.24° ± 0.16° vs. 0.49° ± 0.14°; p=0.001) and setup time by approximately 40% (7 min 48 s vs. 19 min 37 s; p<0.001) compared with MVCT. Dosimetric analysis revealed improved D99% recovery in CTVs with RCD correction (e.g., CTV3: 24.74 Gy with RCD vs. 23.89 Gy without correction, against a reference of 24.74 Gy). ***Conclusion:*** The RCD could provide an effective and accurate solution for correcting pitch and yaw rotational errors during head radiotherapy. This approach enhanced setup precision and efficiency without requiring repeated imaging, thereby improving treatment accuracy in multitarget brain irradiation.

INTRODUCTION

Advanced techniques such as intensity-modulated radiation therapy (IMRT) are widely used to deliver prescribed doses to tumor targets while sparing normal tissues. Image-guided radiation therapy (IGRT) minimizes setup errors, ensures accurate target localization, maximizes tumor control, and reduces complications [1].

In cranial radiotherapy, rotational setup errors can lead to significant dosimetric uncertainties and high reproducibility of patient positioning [2, 3]. This is particularly critical in high-precision treatments such as stereotactic radiosurgery (SRS) where submillimeter accuracy (≤±1 mm) is required to maintain errors in target coverage and dose conformality within ±5% [3, 4].

In radiotherapy for head and neck cancer using tomotherapy, patient positioning is typically guided by lasers and immobilization is achieved using a thermoplastic mask. However, intrafractional head motion may occur despite the use of external immobilization devices [5]. Translational errors along the vertical (Z-direction), lateral (X-direction), and longitudinal (Y-direction) axes, as well as rotational errors, may arise during image registration between megavoltage computed tomography (MVCT) and treatment planning images. Rotational errors in the longitudinal axis (roll) can be corrected by adjusting the initial gantry angle, whereas errors in the vertical (pitch) and lateral (yaw) directions remain uncorrected using conventional methods [6].

Recent advancements and the widespread adoption of surface image-guided radiation therapy (SGRT) have studied in this field. SGRT, a non-invasive technique, employs optical surface imaging (OSI) to monitor patient positioning in real-time using a camera, thereby detecting setup errors without additional radiation exposure [7–9]. However, in cranial radiotherapy, OSI may introduce anatomical bias due to its reliance on external surface anatomy rather than internal structures. Therefore, positioning based solely on the OSI is not recommended [10]. IGRT is preferred for identifying internal cranial anatomy, including normal and tumor tissues, whereas OSI is best utilized for real-time motion monitoring or as an auxiliary tool for patient positioning in clinical practice [11–13].

We developed a rotational correction device (RCD) to overcome the limitations of OSI and address

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the inability of tomotherapy to correct rotational errors, The RCD compensates for the pitch and yaw rotations using six-dimensional error data from the OSI. This approach enables precise correction of pitch and yaw rotations, which are uncorrectable in conventional tomotherapy. This study aimed to evaluate the effectiveness of the RCD in improving the setup accuracy and efficiency of head radiotherapy.

MATERIALS AND METHODS

RCD

The RCD comprised an acrylic adjustment device, a steel adjustment device, and a carbon fiber head baseplate (R605-HCF, Klarity, Guangzhou, China) (figure 1). The acrylic adjustment device included upper and lower acrylic plates. The upper plate allows adjustment of yaw-direction errors up to ± 10° based on OSI guidance (figure 1A). The lower plate was connected to an index bar to ensure consistent positioning during treatment (figure 1B). A resin hinge fabricated using a 3D printer (DM250, Carima, Seoul, Republic of Korea) and a steel adjustment device were installed between the upper acrylic adjustment plate and carbon fiber baseplate, enabling correction of pitch direction errors within ±2.5° (figure 1C).

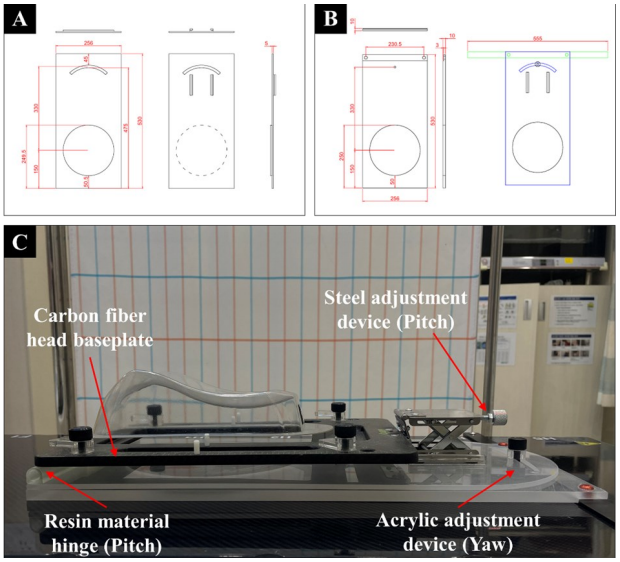


Figure 1. Rotational correction device (RCD) for pitch and yaw errors. A and B each depict the top and bottom plates of the acrylic adjustment device, respectively. C displays the carbon fiber head baseplate and manufactured devices that adjust pitch (steel adjustment device and resin hinge) and yaw (acrylic adjustment device).

Evaluation of MVCT and RCD system utility

Treatment planning

An anthropomorphic head-and-neck phantom (Accuray Inc., Sunnyvale, CA, USA) was positioned on the RCD and immobilized using a thermoplastic mold mask (RT-1876KSGDGLF; Qfix, Avondale, Pennsylvania, USA) for radiation treatment planning. The mask was designed to cover the forehead and chin, while leaving the anterior portion of the face open (figure 2). To minimize OSI measurement errors caused by surface reflection from the phantom, medical tape was used to cover the surface, and a beige-toned makeup product (Air Cushion Intense Cover No. 23 Beige, IOPE, AmorePacific Corp., Seoul, Republic of Korea) was applied to maintain a consistent skin tone reference [14]. RCD was included in the treatment planning images to account for potential dose attenuation.

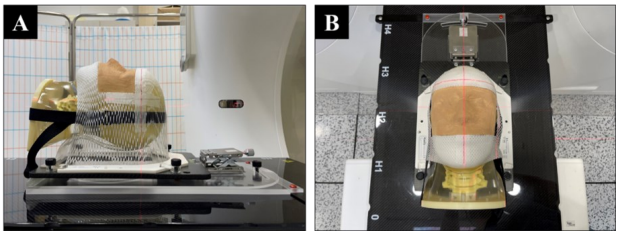


Figure 2. Head phantom setup with a thermoplastic mold mask and rotational correction device, viewed from lateral **(A)** and frontal **(B)** perspectives.

The initial treatment planning reference point (computed tomography [CT] isocenter) was established using simulation room lasers, with three lead indicators aligned in the same axial plane on each side of the phantom forehead. A total of 383 CT images were acquired using a simulation CT scanner (SOMATOM Confidence, Siemens Healthineers, Erlangen, Germany) with a slice thickness of 1 mm. Images were transferred to a tomotherapy treatment planning system (Precision version 3.3.1.3; Accuray Inc., Sunnyvale, CA, USA).

Positional correction and time efficiency

Positional corrections for radiotherapy were performed using the MVCT and OSI (figure 3A, B). To assess the positioning accuracy and time efficiency of each system, a phantom head was randomly placed on the RCD, followed by MVCT image acquisition. The scan range was set to acquire images in the MVCT coarse mode (3 mm), and 70 MVCT images were acquired with an acquisition time of 193.5 s. The MVCT images were automatically registered with the planning CT using a bone and tissue algorithm and were subsequently used for error analysis. In the MVCT system, translation errors were corrected by adjusting the treatment couch based on the analyzed setup error values. Rotational errors were manually corrected by a radiation therapist with over 10 years of clinical experience who removed the thermoplastic mask and repositioned the phantom directly. A follow-up MVCT scan was performed to evaluate the residual setup errors. In the RCD system, setup errors were assessed using the OSI with a commercial SGRT system, AlignRT (Vision RT Ltd., London, UK), and corrections were applied to both the treatment couch and the RCD. Corrections were performed using the

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RCD without removing the mask except in cases with large roll deviations. Ten trials were conducted for each system, with corrections repeated until setup errors were within ±1 mm and ±0.5°. The time required to reach the final position was recorded. The magnitudes (MAG) of the translational (X, Y, and Z) and rotational (roll, pitch, and yaw) vectors were calculated using equations (1) and (2), and a comparative analysis was performed [15].

$$MAG_{translational} = \Delta_{trans} = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \quad (1)$$

$$MAG_{rotational} = \Delta_{rotational} = \sqrt{\Delta Pitch^2 + \Delta Roll^2 + \Delta Yaw^2} \quad (2)$$

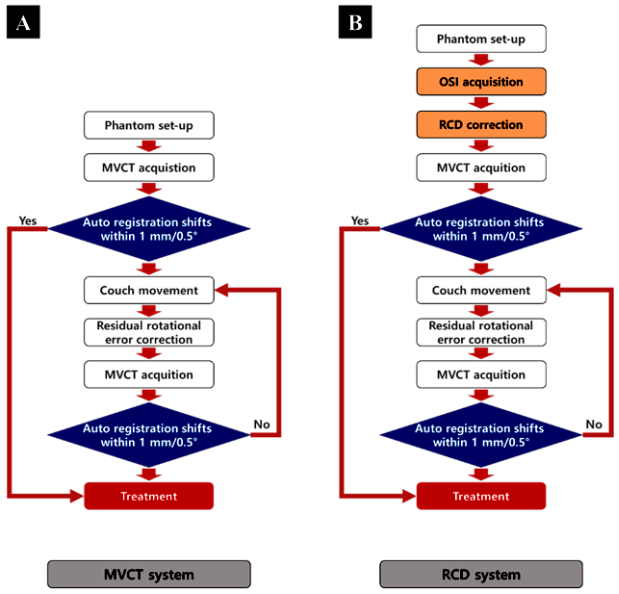


Figure 3. Sequential workflows comparing the conventional setup error correction process using only MVCT with the RCD system utilizing OSI and RCD-based correction. The RCD system involves initial 6D setup error detection via OSI followed by mechanical adjustment of pitch and yaw errors using the RCD. MVCT, megavoltage computed tomography; RCD, rotational correction device; OSI, optical surface imaging.

Treatment planning and evaluation

Treatment plans were developed using a tomotherapy planning system to analyze the differences in dose distribution. Three spherical clinical target volumes (CTVs) were generated to evaluate the effects of rotational errors on the tumor size. CTV1 and CTV2 had a diameter of 30 mm and a volume of 14.1 cm^3, whereas CTV3 had a diameter of 10 mm and a volume of 0.52 cm^3. CTV2 and CTV3 were positioned approximately 60 mm away from CTV1 in opposite directions within the same axial plane. A dose of 25 Gy was prescribed over five fractions based on the D99% (dose delivered to 99% of the target volume) criterion for each CTV [16]. The field width, pitch, and modulation factor were set to 2.5 cm, 0.287 and 2.4, respectively, during treatment planning.

To evaluate the changes in dose distribution under a worst-case scenario, a 3° yaw-directional setup error was intentionally applied based on prior studies [3, 16–18]. Figure 4 shows the dose assessment procedure. In the first step, a 3° yaw directional error was intentionally applied to the head phantom, an MVCT scan was acquired, and the dose distribution from the treatment plan was evaluated without correcting the yaw error. In the second step, the 3° yaw error was corrected using the OSI-guided positional information and RCD. A new MVCT scan was acquired in the corrected state, and the dose distribution of the treatment plan was reevaluated. Differences in D99%, a key indicator of treatment plan accuracy, were analyzed using dose-volume histograms (DVHs). This study primarily aimed to maintain the same D99% dose as used in the reference treatment plan.

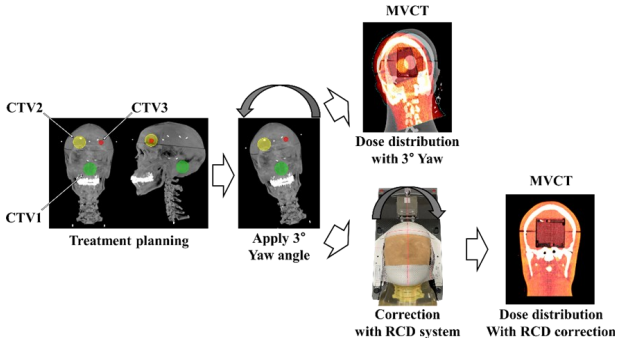


Figure 4. Dosimetric verification of rotational error correction through dose distribution analysis. This procedure evaluates the impact of rotational deviations by comparing the original planning dose with the distributions obtained before and after RCD-based adjustment for a 3-degree yaw error. CTV, clinical target volume; MVCT, megavoltage computed tomography; RCD, rotational correction device.

Statistical analysis

Statistical analyses were performed using the SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). An independent sample t-test was used to compare the MAG_{trans} and MAG_{rot} values between the two systems. The Mann–Whitney U test was used to analyze the time required for final positioning, as the data did not follow a normal distribution. For all statistical tests, significance was set at $p<0.05$.

RESULTS

Positional correction and time efficiency

The mean MAG_{trans} vector values were 0.84 ± 0.28 mm (median: 0.85 mm, range: 0.36-1.45 mm) for the MVCT system and 0.65 ± 0.25 mm (median: 0.70 mm, range: 0.24-0.95 mm) for the RCD system, with no statistically significant difference observed ($p>0.05$) (Table 1). By contrast, the mean MAG_{rot} vector values were 0.49 ± 0.14° (median: 0.52°, range: 0.28–0.69°) for the MVCT system and 0.24 ± 0.16° (median: 0.23°, range: 0.00-0.42°) for the RCD system, indicating significantly greater accuracy with the RCD system ($t=3.860$, $p<0.01$).

Setup time efficiency

The MVCT system required an average of 3.6

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MVCT scans (range: 2-5) to achieve correction within ±1 mm for translational errors and ± 0.5° for rotational errors, whereas the RCD system required an average of 1.3 scans (range: 1-2). Additionally, the average time required for patient positioning was 19 min 37 s ±5 min 19 s (median: 19:34, range: 10:18–26:35) with the MVCT system and 7 min 48 s ±2 min 31 s (median: 6:42, range: 5:19-11:54) with the RCD system, reflecting a statistically significant reduction of approximately 60% in setup time with the RCD system (Z = −3.553, p<0.001) (table 2).

Table 1. Independent samples t-test results for translational and rotational vector magnitude values in the MVCT and RCD systems.

Parameter		Mean±SD	Median	Min	Max	*t*	*p*
MAG_{trans} (mm)	MVCT system	0.84±0.28	0.85	0.36	1.45	1.517	0.147
	RCD system	0.65±0.25	0.70	0.24	0.95		
MAG_{rot} (°)	MVCT system	0.49±0.14	0.52	0.28	0.69	3.860**	0.001
	RCD system	0.24±0.16	0.23	0.00	0.42		

MAGtrans, translational vector magnitude; MAGrot, rotational vector magnitude; MVCT, megavoltage computed tomography; RCD, rotational correction device; SD, standard deviation; Min, minimum; Max, maximum. **p<0.01.

Table 2. Results of the Mann-Whitney U tests for time efficiency between the MVCT and RCD systems.

Parameter		Mean± SD	Median	Min	Max	Z	p
Set-up time (min: s)	MVCT system	19:37±5:19	19:34	10:18	26:35	-3.553***	*p*<0.001
	RCD system	7:48±2:31	6:42	5:19	11:54		

min, min; s, second; MVCT, megavoltage computed tomography; RCD, rotational correction device; SD, standard deviation; Min, minimum; Max, maximum. ***p<0.001.

Treatment plan verification

Without rotational error correction (reference condition), the dose distribution for CTV1 was comparable to that of the original treatment plan, whereas CTV2 and CTV3 showed deviations. After correcting the setup errors using the RCD system, the dose distributions for all the CTVs were aligned with those of the original treatment plan (figure 5).

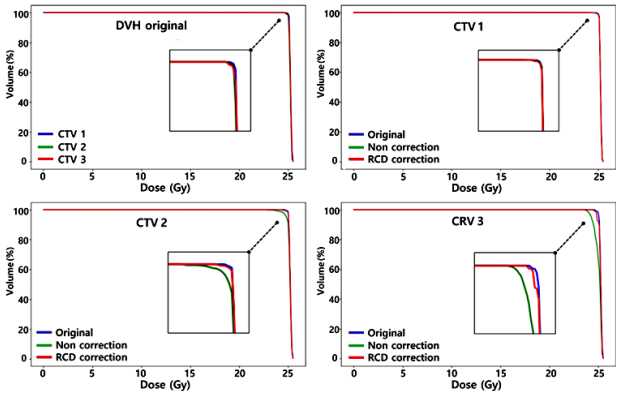


Figure 5. Dose-volume histogram (DVH) analysis for clinical target volumes (CTVs) under a 3° yaw-directional setup error. The comparison between the original treatment plan, non-corrected, and RCD-corrected conditions demonstrates that while dosimetric deviations were most pronounced in CTV2 and CTV3 in the non-corrected state, the RCD effectively restored these dose distributions to the intended levels comparable to the original plan, ensuring target coverage and conformality.

DVH and dose analysis revealed that with a 3° yaw -directional setup error, the D99% values in the MVCT system were 25.03 Gy for CTV1, 24.02 Gy for CTV2, and 23.89 Gy for CTV3-representing reductions of 0.12%, 3.88%, and 3.44%, respectively, compared with the original treatment plan. With the RCD system, the D99% values were 24.95 Gy for CTV1, 24.85 Gy for CTV2, and 24.74 Gy for CTV3, corresponding to reductions of 0.44% for CTV1 and 0.56% for CTV2, whereas CTV3 showed no difference compared with the original treatment plan (table 3). The mean doses after RCD correction were restored to 25.23 ± 0.09 Gy, 25.21 ± 0.12 Gy, and 25.22 ± 0.15 Gy for each CTV, aligning closely with the original planning values.

Table 3. Dose and D99% results for each CTV under the standard treatment plan (original), with a 3° yaw error (non-corrected), and with RCD correction.

Parameter		Max dose (Gy)	Min dose (Gy)	Mean dose (Gy)	D99% (Gy)
CTV1	Original	25.45	24.58	25.23±0.08	25.06
	Non-corrected	25.44	23.76	25.23±0.09	25.03
	RCD-corrected	25.44	24.16	25.23±0.09	24.95
CTV2	Original	25.56	24.64	25.22±0.11	24.99
	Non-corrected	25.56	22.52	25.16±0.24	24.02
	RCD-corrected	25.55	24.11	25.21±0.12	24.85
CTV3	Original	25.45	24.68	25.25±0.12	24.74
	Non-corrected	25.43	23.44	25.03±0.35	23.89
	RCD-corrected	25.43	24.48	25.22±0.15	24.74

Max, maximum; Min, minimum; CTV, clinical target volume; RCD, rotational correction device; Gy, Gray; D99%, dose delivered to 99% of the target volume.

DISCUSSION

Treatment couches with six degrees of freedom (6DoF) were developed to minimize the setup errors in radiation therapy. However, the compatibility with such systems is limited to many treatment machines [19]. Manual adjustments by operators are necessary when without a 6DoF couch, which prolongs the setup time and reduces the positioning accuracy [20]. Robotic setup-correction devices capable of 6D correction have been introduced to address these limitations [16, 21, 22]. Studies have explored the integration of robotic correction devices with OSI systems to enhance the positioning accuracy in radiation therapy [16, 23].

In the MVCT system, correcting the rotational errors in the pitch and yaw directions requires removing the thermoplastic mask, which may introduce random errors during reapplication. Manual adjustments are time consuming and often require additional imaging [20]. Consequently, the MVCT system can require up to five repeated correction steps. In contrast, the RCD system, utilizing initial OSI error assessment and RCD-based correction, achieved setup accuracy within the predefined thresholds of ±1 mm and ±0.5° in seven of ten trials. Target coverage is significantly compromised when rotational errors exceed 0.5° [3, 4,

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[18]. Although target coverage above 95% can be maintained within a ±0.5° rotational error margin, the risk of inadequate coverage increases with larger errors [23]. This study adopted thresholds of ±1 mm for translational and ±0.5° for rotational errors. In three RCD system trials, deviations slightly exceeded these thresholds, reaching up to 1 mm translationally and -0.6° rotationally. When evaluated against the stringent acceptance criteria, these deviations were considered minimal and clinically insignificant.

Prolonged treatment duration may increase patient discomfort, elevating the risk of involuntary movements and necessitating more frequent imaging or larger treatment margins [13, 24]. Tarnavski *et al.* [25] have emphasized the importance of minimizing image processing, registration, and treatment times and noted that treatment errors were significantly reduced when the treatment duration was <5 min. In this study, the MVCT system required an average positioning time of approximately 19 min and 37 s, whereas the RCD system reduced this to 7 min and 48 s, achieving a statistically significant 40% reduction in setup time (p<0.001). Positioning based solely on MVCT complicates the accurate correction of rotational errors and may introduce additional translational errors during the correction process. In contrast, the RCD system corrects positional errors using OSI-derived values. In tomotherapy, IGRT and treatment employ a helical technique with treatment times are relatively long [10, 26]. However, the RCD system enables patient positioning in less time without requiring repeated MVCT scans [10] with improving both setup time and positioning accuracy. Rotational setup errors influenced dose distribution. Park *et al.* [27] evaluated the dosimetric impact of rotational setup errors in patients with brain tumors undergoing volumetric modulated arc therapy with a 6DoF treatment couch. Mean dose differences by region of interest before and after rotational correction revealed a maximum dose difference of up to 2.17 Gy and a mean dose difference of 0.28 Gy in the brain, indicating that dose variations occur when rotational errors were corrected using a 6DoF treatment couch. Rotational setup errors are particularly critical in multitarget radiotherapy, especially for small targets located at greater distances [2, 28]. In addition, the interdependence of translational and rotational movements highlights the importance of minimizing rotational errors to improve overall setup accuracy [29, 30]. In this study, the final rotational vector error was 0.49 ± 0.14° with the MVCT system and 0.24 ± 0.16° with the RCD system with a statistically significant difference (p<0.01). The RCD system corrected rotational errors more rapidly and resulted in lower residual errors. The precision of the OSI in correcting rotational errors can be attributed to the robust registration algorithms in SGRT systems [10, 31].

A 3° yaw directional error was applied to assess its impact on the target coverage based on the findings of Usui *et al.* [16]. Dose distribution deviations were observed for CTV2 and CTV3. However, both the dose distribution and D99% values closely matched those of the reference treatment plan after correction with the RCD. Therefore, yaw-directional rotational errors could be effectively corrected using the RCD. The RCD correction method may be effective even under complex dose distribution conditions and could enhance treatment accuracy. However, Usui *et al.* [16] have reported a 10% improvement in D99% following rotational error correction, whereas this study observed a modest improvement of <4%. This difference may stem from variations in target distance, angular positioning, and coplanar positioning of CTV2 and CTV3, which likely influenced the treatment planning outcomes. Various clinical scenarios should be considered when applying these findings in clinical practice.

This study has some limitations. The setup errors were analyzed using a phantom. OSI is highly applicable to head radiotherapy because of the rigidity of the skull [10]; however, unlike phantoms, the human facial surface is deformable. Thus, clinical implementation requires careful monitoring of patient weight changes and facial morphology [32,33]. Additionally, the analysis was limited to head treatments using tomotherapy, which is a system without rotational correction capabilities.

Future research should prioritize real-time position correction technologies, as demonstrated by Ostyne *et al.* [21], who integrated robotic motion with an optical tracking system and a control computer. Automated positioning via numeric input could enhance user convenience and significantly improve the precision of rotational delivery, particularly when compared to manual methods.

CONCLUSION

The time and number of procedures required for IGRT was efficiently reduced using an RCD. The RCD utilized the OSI error information to correct pitch and yaw directional errors, which are not addressed in head radiotherapy with tomotherapy. In particular, the RCD improved the accuracy of rotational setup correction, which is critical for multitarget treatment of the head. Given the pivotal role of patient positioning and posture in radiotherapy efficacy, this approach could facilitate more precise treatment delivery.

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***Ethical considerations*:** This study was conducted using a phantom; therefore, institutional review board approval was not required.

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authors declare that no artificial intelligence tools were used during the preparation of this manuscript.

***Author contributions*:** D.K. and S.K., designed the experiments and wrote the manuscript. K.K. and J.J., designed the experimental equipment, performed statistical analyses and summarized the results. D.K. and K.C., designed the treatment plans. All the authors reviewed and edited the manuscript. S. Kim supervised this study.

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