



Independent Six-degree-of-freedom Accuracy Evaluation of BrainLab ExacTrac Dynamic and Varian CBCT Systems in Stereotactic Radiotherapy Using a Couch-based Reference

Deniz YALMAN, Emin TAVLAYAN, Yusuf Ziya HAZERAL, Nezahat OLACAK, Serra KAMER

Department of Radiation Oncology, Ege University Faculty of Medicine, İzmir-Türkiye

OBJECTIVE

The study aims to evaluate the imaging and positioning accuracy of the BrainLab ExacTrac Dynamic System integrated with the Varian TrueBeam Linear Accelerator for stereotactic radiotherapy.

METHODS

BrainLab ExacTrac Dynamic System, BrainLab Phantom Pointer, and BrainLab Head Phantom were utilized. Imaging and positioning accuracy were assessed through manual and couch-induced displacement tests. This article does not contain any studies with human participants or animals performed by any of the authors. Ethical approval was not required for this study as it was conducted using phantoms only.

RESULTS

The study evaluated the accuracy of BrainLab ETD and Varian cone-beam computed tomography (CBCT) systems using a shared reference. Both systems demonstrated sub-millimeter precision, with translational errors ranging between 0.06 mm (ETD Z-axis) and 0.04 mm (ETD X-axis), and rotational errors below 0.12°. Maximum observed errors did not exceed 0.3 mm for translational or 0.2° for rotational movements. For combined errors 3D translational accuracy showed no significant difference ($p=0.482$) between ETD (0.11 mm) and CBCT (0.09 mm). The 6D error magnitude was slightly lower for ETD (0.14 mm vs. 0.20 mm, $p<0.001$). Correlation analysis revealed that single-axis correlations between ETD and CBCT were not significant ($p>0.05$) except for pitch errors ($p=0.023$), which showed moderate correlation. The mean DIFF 6D vector (0.23 mm), representing the positional offset between ETD and CBCT detections, was significantly larger than both ETD 6D and CBCT 6D errors ($p<0.001$ and $p=0.002$, respectively).

CONCLUSION

Both systems offer high precision in detecting positional shifts. The ETD System's ability to provide continuous, real-time monitoring enhances patient safety by allowing real-time correction of positioning errors, making it a valuable tool for stereotactic radiotherapy applications. Further studies with patient data are needed to validate the clinical application of these findings.

Keywords: Cone-beam computed tomography; ExacTrac dynamic; stereotactic radiation therapy.

Copyright © 2026, Turkish Society for Radiation Oncology

Received: November 03, 2025

Accepted: December 05, 2025

Online: March 02, 2026

Accessible online at:

www.onkder.org

Dr. Deniz YALMAN

Ege Üniversitesi Tıp Fakültesi,

Radyasyon Onkolojisi Anabilim Dalı,

İzmir-Türkiye

E-mail: deniz.yalman@ege.edu.tr



INTRODUCTION

Stereotactic radiotherapy (SRT) has significantly advanced the treatment of intracranial and extracranial lesions by enabling the precise delivery of high radiation doses while minimizing exposure to surrounding healthy tissues. The effectiveness of SRT is critically dependent on the accuracy of the imaging and positioning systems used during treatment.[1–3] With the development of advanced imaging technologies such as cone-beam computed tomography (CBCT) and sophisticated linear accelerators, the precision and efficacy of SRT have been substantially enhanced.[4,5] However, the continuous evaluation of these systems' imaging and positioning accuracy is essential to ensure optimal treatment outcomes.

In recent years, the integration of imaging systems like the BrainLab ExacTrac Dynamic (ETD) Imaging System with linear accelerators such as the Varian TrueBeam STX has further refined SRT capabilities. These systems provide real-time imaging and positioning adjustments, allowing for highly accurate target localization and dose delivery.[4,6] Despite these technological advancements, rigorous calibration and quality assurance (QA) protocols remain imperative to maintain the precision of these sophisticated systems.

Numerous studies have underscored the importance of regular calibration and QA checks in maintaining the accuracy of SRT systems. The use of phantoms and specialized QA tools, such as the Varian Machine Performance Check (MPC) software and the BrainLab Phantom Pointer, has been instrumental in verifying the alignment and performance of imaging and treatment delivery components.[7,8] Calibrating kV and MV imaging systems, along with ensuring the precise alignment of isocenters, is crucial for accurate radiation dose targeting.[9,10]

This study aims to provide a comprehensive evaluation of the imaging and positioning accuracy of SRT systems using a series of calibration and QA tests. By employing tools such as the BrainLab Phantom Pointer, BrainLab Head Phantom, and various displacement tests, we seek to validate the precision of these systems in clinical settings. Our methodology includes detailed calibration routines for CBCT, MV, and kV imaging systems, as well as performance checks using the Varian MPC software. Additionally, we assess the systems' response to manual and couch-induced displacements to thoroughly examine their accuracy under different conditions.

The findings of this study will contribute to the existing body of knowledge on the importance of stringent QA protocols in SRT. By ensuring that all mechanical and dosimetric settings are accurately cali-

brated, this research aims to enhance the reliability of stereotactic treatments and improve patient outcomes. This work underscores the critical role of continuous quality assurance in the evolving landscape of radiation oncology, highlighting the necessity of meticulous calibration and evaluation practices to maintain the high standards required for effective cancer treatment.

MATERIALS AND METHODS

Hardware and Software

The study utilized two linear accelerators: the Varian TrueBeam STX Linear Accelerator and the Varian TrueBeam Linear Accelerator (Varian Medical Systems, Palo Alto, CA, USA). For imaging systems, the BrainLab ExacTrac Dynamic Imaging System (BrainLab, Munich, Germany) and GE Discovery RT Computed Tomography Simulator (GE Healthcare, Chicago, IL, USA) were employed. Treatment planning was conducted using the Eclipse 16.1 Treatment Planning System (Varian Medical Systems, Palo Alto, CA, USA) and the Elements 2.0 Treatment Planning System (BrainLab, Munich, Germany). Quality assurance and calibration were ensured using the BrainLab Phantom Pointer (Ball-Bearing), BrainLab Head Phantom, and ISO Cube Phantom (Standard Imaging, Middleton, WI, USA).

Calibration and Quality Control

Imaging Systems Calibration

Initial calibration routines were performed to enhance the imaging quality of both linear accelerators. These included dark field and flood field calibrations, identification and exclusion of dead detector pixels, and adjustment of kV collimator jaw settings. Subsequently, similar calibration processes were carried out for the CBCT system. The isocenters of the kV and MV imaging systems were aligned with the isocenter of the linear accelerator using the Varian IsoCal phantom. By rotating the gantry through 360 degrees and capturing images, any deviations of the geometric center from the device's central axis were detected and corrected.

Machine Performance Check (MPC)

The MPC involved comprehensive mechanical and dosimetric tests of the treatment devices. The Varian MPC software and MPC check phantom were used to conduct numerous quality control tests, including checks on gantry, collimator, and couch alignment, as well as the accuracy of the jaws and MLC positions. These tests ensured that all calibrations were verified and met established limits before starting the measurements.

Picket Fence and Winston-Lutz Tests

To verify the positional accuracy of the MLCs and optimize the success rate of the Hancock Winston-Lutz test, the picket fence test was conducted. Using the Eclipse planning system, plans were created at gantry angles of 0, 90, 180, and 270 degrees, covering all MLCs. Each plan included a defined irradiation time of 20 MU for each subfield, ensuring proper alignment and gaps between MLC pairs.

The Hancock Winston-Lutz test involved creating twelve different areas with 6 MV photon energy, incorporating specific gantry, couch, and collimator angles. Each area was designed to prevent leakage doses by positioning the MLC intersection areas outside the radiation field. The BrainLab phantom pointer (ball-bearing) was positioned according to the light field centers at gantry angles of 0 and 90 degrees. Port images obtained from the irradiation were analyzed using the SNC Machine software, and necessary corrections were applied. The device's isocenter was then radiologically positioned with high precision, and the BrainLab ETD system was calibrated to this point.

Evaluation of Imaging and Positioning Accuracy

Before evaluating the imaging and positioning accuracies of the stereotactic radiotherapy systems, all mechanical and dosimetric settings of the treatment devices were verified for accuracy, and necessary adjustments were made. The isocenters of both systems were precisely calibrated.

BrainLab Phantom Pointer (Ball-Bearing) Tests

Manual Displacement Test

We moved the ball-bearing (BB) in one direction in 3D space to a known distance “d” and measured the displacement (Fig. 1). Keeping the first displacement, we then moved the BB the same amount in the second direction and measured again. Subsequently, we moved the BB to the distance “d” in the third direction and measured once more. The final coordinate after the third measurement was (d, d, d). We repeated this process with negative “d” values, creating a set of six measurements for each selected distance. We performed this method using distances of 0.1 mm, 0.5 mm, 1.5 mm, and 3.0 mm, resulting in a total of 24 measurement sets. The aim of this method was to utilize varying distances to test the detection abilities of the systems and to cover the full 3D space as homogeneously as possible.

Couch Displacement Test

Following the manual displacement tests, the BrainLab Phantom Pointer was repositioned to the isocenter,

and displacements were applied using the treatment couch. These displacements were detected both by the BrainLab ETD system and the integrated kV and MV port imaging systems. The responses of the BrainLab ETD system and the kV and MV port imaging systems to these displacements were separately analyzed.

Comparison of Positioning Accuracy with BrainLab ETD and Varian CBCT Using Head Phantom

This part of the study was designed to evaluate the relative accuracy of the BrainLab ETD and Varian CBCT systems in detecting displacements applied via a clinically validated treatment couch. Rather than assuming CBCT as the gold standard, both systems were independently assessed using a shared reference. Translational displacements were validated with a micrometer, while rotational measurements used the treatment couch as a consistent reference. This strategy allows a methodologically unbiased comparison of six degrees of freedom (6DOF) detection capabilities.

The head phantom was fitted with a BrainLab head and neck positioning mask to ensure stability and reproducibility during measurements (Fig. 2). High-resolution CT images with a slice thickness of 0.625 mm were acquired and imported into the Eclipse treatment planning system. A demo plan with a single field, including kV port and CBCT imaging areas, was created and loaded into both the BrainLab ETD and Varian CBCT systems to enable precise positional comparisons.

Couch Displacement Protocol

Couch displacements were systematically applied in four predefined distances of 0.1 mm, 0.5 mm, 1.0 mm, and 3.0 mm along each axis (X, Y, Z). For each distance, displacements were performed in both positive and negative directions, resulting in eight measurements per axis. Rotational displacements (yaw) were also included in the protocol, following the same sequence of movements and distances. Each displacement was performed sequentially, first along the translational axes (X, Y, Z) and then for yaw, ensuring a comprehensive evaluation of the system's 6DOF detection capabilities.

To avoid bias present in previous studies, which often compared ETD directly against CBCT while implicitly treating CBCT as the baseline, this study was designed to measure both systems independently against the same source of displacements: the treatment couch. By using the couch as the reference for both ETD and CBCT, the study evaluated their relative performance on an equal basis.

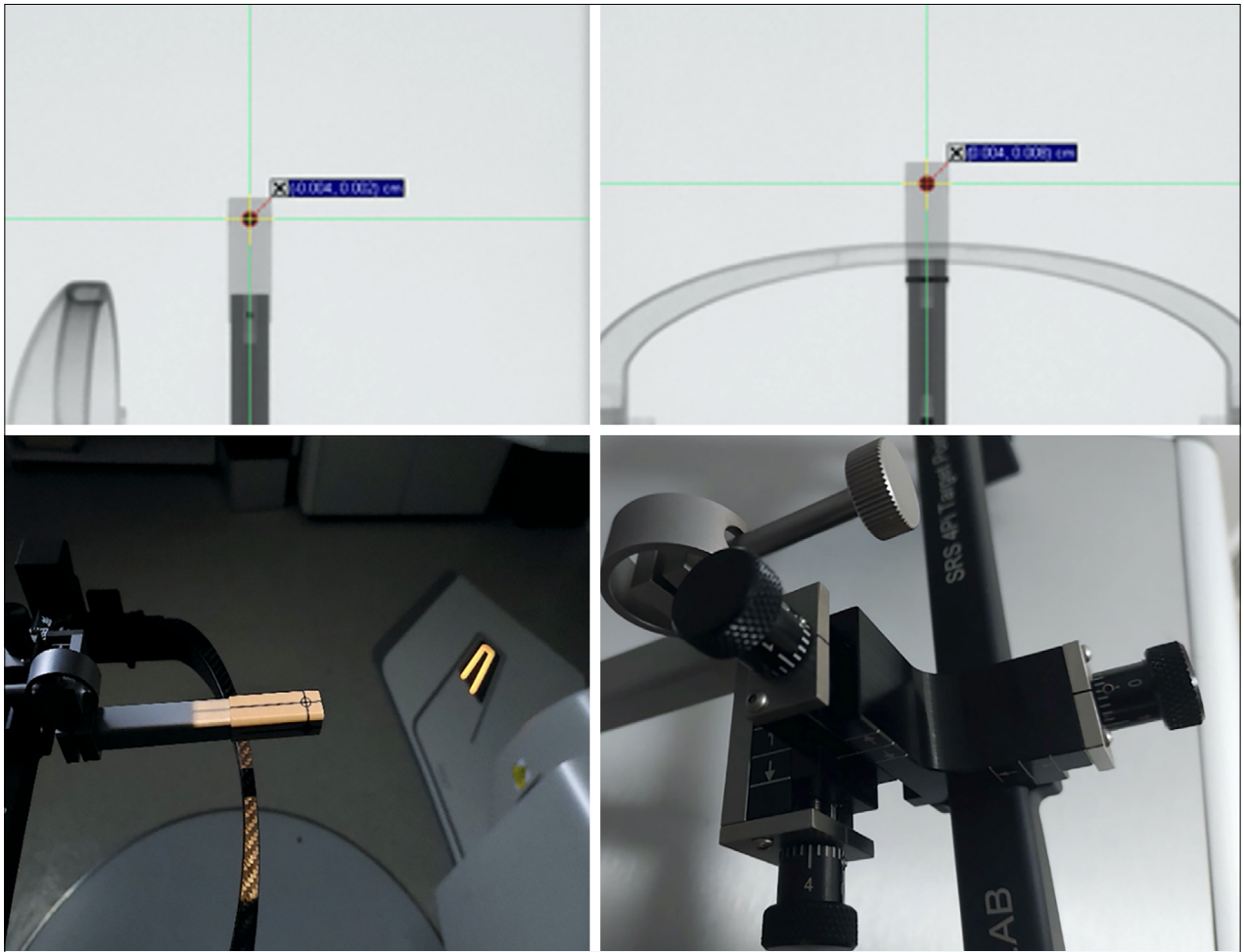


Fig. 1. BrainLab phantom pointer (Ball-Bearing).

Measurement and Data Recording

For each applied displacement, six values were recorded, reflecting positional deviations across all degrees of freedom: translations (X, Y, Z) and rotations (yaw, pitch, roll). Translational displacements were validated against a high-precision micrometer, ensuring accuracy within 0.02 mm. This validation established the treatment couch as a reliable reference for translational movements along the X, Y, and Z axes.

To evaluate rotational detection, displacements were applied along the yaw axis, incorporating the inherent reliability of the treatment couch as the reference. Although the rotational accuracy of the couch was not independently validated, its use as a consistent reference allowed for a relative comparison of the BrainLab ETD and Varian CBCT systems. Yaw rotations were included to evaluate the relative performance of the two systems, rather than to establish absolute rotational accuracy.

For each displacement, the 6D error magnitude (E_{6D}) was calculated using the following formula:

$$E_{6D} = \sqrt{\sum_{i=1}^6 (\Delta i)^2}$$

where Δi represents the deviation in each degree of freedom. This calculation was performed for each applied displacement to provide a comprehensive measure of positional error for both systems.

Statistical Analysis

All data were analyzed using IBM SPSS Statistics (version 29.0.1, IBM Corp., Armonk, NY, USA). Due to the small sample sizes and non-normal distribution of error values (verified via visual inspection and distribution metrics), nonparametric statistical methods were used throughout the study. The Wilcoxon signed-rank test was applied to compare paired er-



Fig. 2. BrainLab head phantom and positioning mask.

ror measurements between systems, and correlation analyses were conducted to evaluate inter-system agreement across individual and combined axes. Statistical significance was defined at $p < 0.05$.

All graphical representations were created using the BoxPlotR web-based tool.[11] (<http://shiny.chemgrid.org/boxplotr>). These boxplots illustrate the distributions and significant differences between the systems and their respective errors, as discussed in subsequent sections.

RESULTS

The following results were obtained from measurements and statistical analyses. Key comparisons are presented for translational and rotational positioning errors across systems.

Micrometer vs ETD Accuracy

ETD system detected all manual displacements of the Ball-Bearing (BB) phantom (0.10–3.00 mm) with 0.02 mm precision, as measured using the integrated micrometer at two-digit sensitivity (0.01 mm resolution). No discrepancies were observed between applied displacements and ETD-reported values, even at the smallest tested increment (0.10 mm).

This confirms the system's reliability for subsequent tests requiring 0.1 mm clinical sensitivity. The results validate ETD's capability to resolve submillimeter positional deviations, ensuring its suitability for high-precision stereotactic radiotherapy quality assurance protocols.

Couch Displacement Detection

The precision of BrainLab ETD, MV and kV imaging systems in detecting couch-induced displacements was evaluated using the Ball-Bearing (BB) phantom. Couch shifts (0.10–3.00 mm) were applied along all translational axes (X, Y, Z) using service mode commands (two-digit precision, 0.01 mm resolution), with displacements recorded by the ETD and orthogonal MV/kV imaging systems at clinical one-digit precision (0.1 mm).

The ETD system detected all 30 couch displacements with 0.1 mm maximum error per axis, mirroring its performance in micrometer-based tests. For MV/kV systems, individual axis errors did not exceed 0.1 mm, and 3D vector errors reached a maximum of 0.14 mm (mean: 0.08 ± 0.04 mm). Wilcoxon signed rank tests confirmed that there were no significant differences between MV and kV systems ($p > 0.05$), with errors exhibiting random distribution (no inter-system correlation, $r < 0.2$) (Fig. 3).

These results validate the treatment couch as a reliable reference for submillimeter positional adjustments in clinical workflows. The consistency between the ETD, MV, and kV systems underscores their collective precision for stereotactic radiotherapy applications that require a tolerance of 0.1 mm.

Head Phantom Movements

Translations and Rotations Detected by ETD and CBCT

The descriptive statistics for positional errors demonstrated submillimeter precision across both the ETD

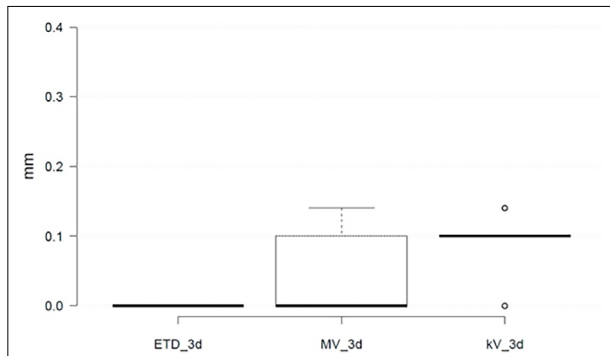


Fig. 3. Boxplot comparing 3D errors detected by ETD, MV, and kV systems during couch-induced displacements of the Ball-Bearing phantom.

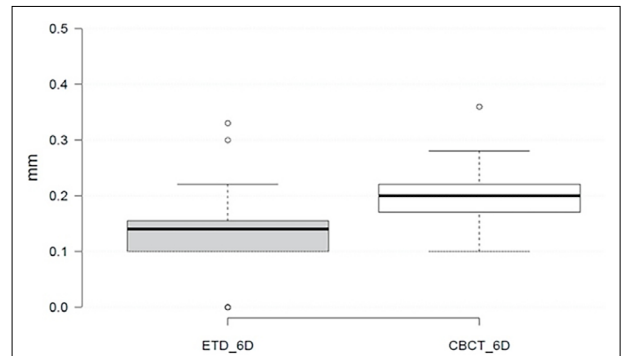


Fig. 5. Boxplot comparing combined 6D errors, integrating translational and rotational deviations, for ETD and CBCT systems.

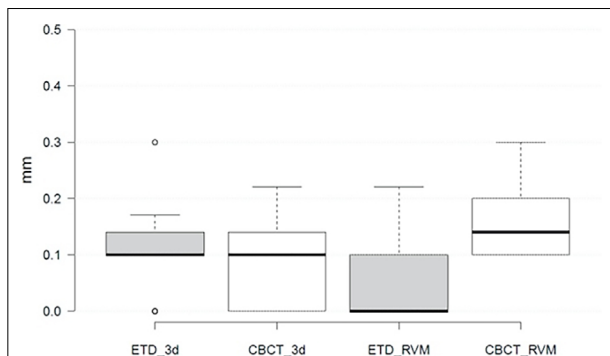


Fig. 4. Boxplot comparing 3D translational errors and rotational vector magnitude (RVM) errors for ETD and CBCT systems.

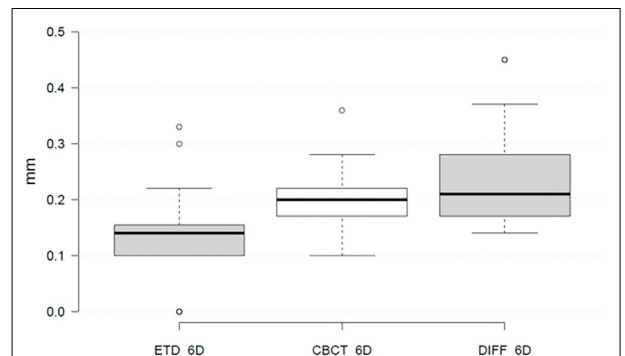


Fig. 6. Boxplot illustrating the DIFF6D vector, representing positional offsets between ETD and CBCT detections, with potential impact of bias.

and CBCT systems. For translational axes, mean errors ranged between 0.06 mm (ETD Z axis) and 0.04 mm (ETD X axis), with standard deviations <0.07 mm. Rotational errors were similarly minimal, with mean deviations $<0.12^\circ$ and standard deviations $<0.07^\circ$. The maximum observed errors did not exceed 0.3 mm or 0.2° , underscoring the high precision of both systems.

Although significant differences ($p < 0.05$) were observed for specific axes (e.g., ETD demonstrated smaller errors in Y/Z translations and pitch rotations, CBCT on the X axis and yaw), the absolute error magnitudes were clinically negligible. For example, the mean difference in the Y-axis errors between ETD and CBCT was 0.04 mm, and the pitch rotation discrepancies averaged 0.09° .

For combined errors, 3D translational accuracy showed no significant difference between systems ($p = 0.482$), with mean errors of 0.11 mm (ETD) and 0.09 mm (CBCT). The boxplots for translational errors (X, Y, Z) and rotational vector magnitude (RVM) errors (Fig. 4) further emphasize the sub-millimeter

precision of both systems, highlighting minimal variability and similar error ranges across axes.

The 6D error magnitude, incorporating translational and rotational deviations, was slightly lower for ETD (0.14 mm vs. 0.20 mm, $p < 0.001$). The boxplot depicting 6D error magnitude (Fig. 5) demonstrates a statistically significant difference between ETD and CBCT ($p < 0.001$), with ETD achieving lower combined translational and rotational error magnitudes. The correlation analysis showed that 5 of 6 single-axis correlations between ETD and CBCT were not statistically significant ($p > 0.05$), indicating no meaningful agreement. Although, pitch errors were moderately correlated ($p = 0.023$), suggesting some level of agreement for this axis. Despite this single-axis correlation, the overall lack of significant relationships across axes underscores the systems' independent error detection and operational differences.

For the combined 6D error, which integrates translational and rotational deviations, the correlation co-

efficient was not significant ($p=0.653$). This highlights the independent detection of 6D errors by the two systems, with no systematic relationship observed across the overall error magnitudes. These findings emphasize the robustness of both systems for stereotactic radiotherapy, with clinically negligible differences in precision. The correlation analysis further supports the conclusion that ETD and CBCT systems independently achieve high accuracy in positional detection, with minor variations likely attributable to system-specific operational characteristics rather than systematic biases.

Comparison of ETD and CBCT Error Magnitudes Using a Difference Vector

Our study evaluated both the ETD and CBCT systems against a shared reference, a phantom displaced by the treatment couch and we showed that both systems achieve sub-millimeter precision in error detection. While some prior literature assumes CBCT as the ground truth, this methodology may lead to inaccurate estimations of error magnitudes when comparing ETD detections directly to CBCT. This can exaggerate the magnitude, as the difference reflects not only the magnitude but also the directional offset between the two systems. Conversely, if the vectorial directions of ETD and CBCT errors align closely, the magnitude may appear artificially reduced, masking the true extent of discrepancies. To evaluate the discrepancy, we computed a difference vector (DIFF-6D), representing the positional offset between ETD and CBCT detections. The mean DIFF-6D was 0.23 mm, larger than both ETD-6D and CBCT-6D. Statistical analysis confirmed that the DIFF-6D vector was significantly greater than the 6D errors of ETD and CBCT systems ($p<0.001$ and $p=0.002$ respectively) (Fig. 6).

These results highlight the potential overestimation of ETD errors when compared directly to CBCT without an independent reference. While CBCT remains a clinically indispensable tool due to its anatomical visualization capabilities, our findings emphasize the importance of unbiased methodologies for evaluating detection capabilities of imaging systems.

DISCUSSION

Due to the use of high doses with a small number of fractions and small PTV margins in SRS/SBRT treatment techniques, correct patient positioning is extremely important to prevent complications in surrounding tissues and organs at risk and to ensure tumor control. [1,2,4,9,10] Correct patient positioning

(setup) before treatment is essential to reduce doses to organs at risk while delivering the prescribed dose to the tumor.[12,13] A 1–2 mm margin (usually 1 mm) is used for GTV-PTV in brain tumors. It has been reported that larger margins may cause complications such as radiation-induced brain necrosis. V12Gy should be kept below 5 to 10 cc to reduce brain necrosis.[3,14,15] In SRS/SBRT treatment techniques, precise patient positioning and/or sub-millimeter accuracy monitoring is required due to small PTV margins and potential patient movements.[1]

Since thermoplastic masks do not completely eliminate potential movements during stereotactic treatments, patient motion of varying magnitudes may occur between each arc of dose delivery, which can lead to overdosing of normal tissues near the target.[5,16] Although CBCT, widely used before treatment in IGRT, provides three-dimensional anatomical images, it cannot track intrafractional/interfractional movement during treatment. A real-time intrafractional patient tracking system capable of optical surface scanning has been developed, but these systems lack internal anatomy information. In our clinic, the “ExacTrac Dynamic (ETD)” system is used, which includes X-ray tubes and flat panel detectors. This system monitors changes in patient anatomy or positioning independently of the treatment device’s parameters and corrects any discrepancies. The ETD system also offers 3D optical surface scanning and thermal monitoring, providing verification methods beyond treatment devices alone.[4]

Setup and intrafraction movements can be corrected using the ExacTrac X-ray 6D imaging system, allowing for reduced GTV-PTV margins.[3] The ExacTrac system detects uncertainties caused by translational and rotational movements, allowing for verification and correction before and during treatment. It offers advantages over CBCT, such as shorter image acquisition times and lower patient radiation exposure.[5] For example, one study found a simultaneous radiation dose of 2.0 mSv with ExacTrac compared to 14.0 mSv with CBCT.[17]

CBCT is essential in all radiotherapy treatments due to its superior visualization of anatomical structures and soft tissues, offering 3D and transaxial images before treatment. Geometric uncertainties are detected more clearly in SRS/SBRT through integrating multiple imaging techniques.[18] Proper and accurate IGRT techniques must be used to detect intrafraction and interfraction errors.[13] Additionally, correct positioning of the radiation isocenter during gantry, collimator, and couch rotation depends on the use of accurate IGRT techniques.[1]

In SRS for multiple brain metastases, correct isocenter positioning during treatment is crucial to ensure precise dose delivery to all targets.[3] Rotational uncertainties in single-isocenter SRS techniques can significantly impact target coverage for lesions located far from the isocenter.[1]

To determine the accuracy of the ExacTrac system, the first step is to verify patient positioning accuracy relative to the linear accelerator isocenter. Secondly, imaging and couch corrections must be confirmed. [5] Calibration of the ExacTrac isocenter is regularly performed using a special 10x10 cm² phantom with a reflective sphere, ensuring alignment with the linear accelerator isocenter.

A Winston-Lutz (WL) phantom, with a small metal sphere inside, is used to determine the ExacTrac X-ray isocenter relative to the radiation isocenter. The difference between the sphere's center projection and the treatment area center should be <0.7 mm.[10] Arp & Carl[8] found deviations between the outer laser isocenter and the ExacTrac isocenter ranging from 0.21 to 0.42 mm, while the difference between the laser isocenter and radiation isocenter ranged from 0.37 to 0.83 mm. The three-dimensional deviation between the radiation isocenter and the ExacTrac center was between 0.31 and 1.07 mm. Verellen et al.[19] reported a deviation of 0.24 mm at the radiation isocenter using hidden target tests.

In our study, we determined the radiation isocenter using similar methods. After examining the 2D images taken at different gantry, collimator, and couch angles, the radiation isocenter was determined by shifting the metal sphere on the ETD phantom with micrometer precision. The BB phantom provided with the ETD system was used to ensure sub-millimeter accuracy in detecting the isocenter, showing minimal deviation. The ETD system performed accurately in all measurements taken at 90 different points, detecting the BB without error, with maximum deviations of 0.1 mm from the radiation isocenter.

Verbakel et al.[7] reported a deviation of 0.3 mm in each direction after randomly positioning an Alderson head phantom 31 times and performing automatic 6D couch shifts using ExacTrac. Intrafraction movement was measured at 0.35±0.21 mm (maximum 1.15 mm) for 46 patients. Wurm et al.[20] found an average translational and rotational setup error of 0.31 mm and 0.26°, respectively. Jani et al.[21] reported a positional accuracy of <1 mm with ExacTrac in 94 patients, emphasizing the importance of real patient data in understanding intrafractional motion. Gevaert et al.[9] validated the ExacTrac/Novalis Body system on an anthropomorphic phantom,

reporting rotational setup errors with longitudinal precision of 0.09°±0.06° and lateral precision of 0.02°±0.07°.

When comparing ExacTrac and CBCT in terms of setup errors, ExacTrac showed more accurate results. Chow et al.[4] compared the positional shifts detected by ExacTrac's optical surface thermal monitoring (EXTD-thml) with stereoscopic X-ray (EXTD-X-ray) and CBCT. The translational differences between ExacTrac-thml and CBCT were 0.57±0.41 mm for the cranial phantom and 0.66±0.40 mm for the pelvic phantom, while the rotational differences were less than 0.7°.

Kojima et al.[22] reported translational errors of less than 1 mm and rotational errors of less than 1°. Ma et al.[23] determined setup errors between EXTD-X-ray and CBCT using a cranial phantom, finding translational differences of <0.5 mm and rotational differences of <0.2°. In another study, the setup differences between the BrainLab ExacTrac X-ray system and CBCT for intracranial stereotactic radiotherapy were reported as <1.01 mm for online matching and <0.82° for rotational differences.[13] Ma et al.[23] found translational differences of <0.5 mm for phantoms and <1.5 mm for patients, and rotational differences of <0.2° for phantoms and <1.0° for patients. Chang et al.[2] evaluated setup errors between ExacTrac X-ray and CBCT in spinal non-invasive stereotactic body therapy (SBRT), finding translational differences of <1.0 mm and rotational differences of <1.0° for phantoms, while patient data showed differences of <2.0 mm and <1.5°.

Spadea et al.[24] reported intrafraction variability between ExacTrac X-ray and CBCT using IR optical localization, with localization differences of 0.3±0.3 mm and X-ray image differences of 0.9±0.8 mm. Takakura et al.[25] found a positional correction accuracy of 0.07±0.22 mm for a head and neck phantom, while the overall geometric accuracy of the Novalis ExacTrac system was reported as 0.31±0.77 mm.

Li et al.[6] found setup error differences between CBCT and BrainLab ExacTrac X-ray were less than 0.4 mm in the translational direction and 0.5° in the rotational direction. Tanyi et al.[26] reported deviations between ExacTrac and 4D CBCT of 0.40±0.72 mm in the vertical direction and -0.06±0.67 mm in the lateral direction from 245 patient matchings, with rotational differences within 0.7°. Montgomery and Collins[5] reported submillimeter reproducibility for ExacTrac based on hidden target tests.

Since fixed phantoms were used in our study, future studies will compare the performance of these systems with real patient data to further evaluate their clinical applicability.

CONCLUSION

Unlike previous studies that rely on CBCT as the reference standard, this study evaluated the accuracy of BrainLab ExacTrac Dynamic and Varian CBCT systems using an independent reference, a phantom displaced by a micrometer and the treatment couch, to eliminate bias. Both systems demonstrated sub-millimeter precision for translational errors and sub-degree accuracy for rotational deviations, confirming their suitability for high-precision stereotactic radiotherapy. We directly compared 6D error detection accuracy of ETD and CBCT systems against an external reference. Significant differences in 6D error magnitudes were observed between ETD and CBCT, with ETD achieving slightly lower combined errors. Correlation analysis revealed no meaningful agreement for single-axis errors, underscoring the independent error detection capabilities of the systems. The DIFF6D vector, representing positional offsets between the systems, highlighted potential discrepancies when CBCT is assumed as the ground truth, emphasizing the importance of unbiased evaluation methodologies.

While CBCT remains indispensable for anatomical visualization in clinical workflows, this study demonstrates that both ETD and CBCT independently achieve the precision required for stereotactic radiotherapy applications. Future research should further investigate system performance in dynamic clinical scenarios especially in pediatric patients to validate these findings.

Conflict of Interest Statement: The authors declare no direct conflict of interests.

Funding: This study was supported by the Ege University Scientific Research Projects Coordination Unit under Project No. 21799. The authors would like to express their gratitude to Ege University for their financial and institutional support.

Use of AI for Writing Assistance: No AI technologies utilized.

Author Contributions: Concept – D.Y., E.T., Y.Z.H., N.O., S.K.; Design – D.Y., E.T., Y.Z.H., N.O., S.K.; Supervision – D.Y., E.T., Y.Z.H., N.O., S.K.; Data collection and/or processing – E.T., Y.Z.H.; Data analysis and/or interpretation – D.Y., E.T., Y.Z.H.; Literature search – D.Y., E.T.; Writing – D.Y., E.T.; Critical review – D.Y., E.T., Y.Z.H., N.O., S.K.

Peer-review: Externally peer-reviewed.

REFERENCES

1. Eder MM, Reiner M, Heinz C, Garny S, Freislederer P, Landry G, et al. Single-isocenter stereotactic radiosurgery for multiple brain metastases: Impact of patient misalignments on target coverage in non-coplanar treatments. *Z Med Phys* 2022;32(3):296–311
2. Chang Z, Wang Z, Ma J, O'Daniel JC, Kirkpatrick J, Yin FF. 6D image guidance for spinal non-invasive stereotactic body radiation therapy: Comparison between ExacTrac X-ray 6D with kilo-voltage cone-beam CT. *Radiother Oncol* 2010;95(1):116–21
3. Minniti G, Capone L, Alongi F, Figlia V, Nardiello B, El Gawhary R, et al. Initial experience with single-isocenter radiosurgery to target multiple brain metastases using an automated treatment planning software: Clinical outcomes and optimal target volume margins strategy. *Adv Radiat Oncol* 2020;5(5):856–64
4. Chow VUY, Cheung MLM, Kan MWK, Chan ATC. Shift detection discrepancy between ExacTrac Dynamic system and cone-beam computed tomography. *J Appl Clin Med Phys* 2022;23(5):e13567
5. Montgomery C, Collins M. An evaluation of the BrainLAB 6D ExacTrac/Novalis Tx system for image-guided intracranial radiotherapy. *J Radiother Pract* 2017;16:326–33
6. Li J, Shi W, Andrews D, Werner-Wasik M, Lu B, Yu Y, et al. Comparison of online 6 degree-of-freedom image registration of Varian TrueBeam cone-beam CT and Brainlab ExacTrac x-ray for intracranial radiosurgery. *Technol Cancer Res Treat* 2017;16(3):339–43
7. Verbakel WFAR, Lagerwaard FJ, Verduin AJE, Heukelom S, Slotman BJ, Cuijpers JP. The accuracy of frameless stereotactic intracranial radiosurgery. *Radiother Oncol* 2010;97(3):390–4
8. Arp DT, Carl J. EXACTRAC x-ray and beam isocentres—what's the difference? *Med Phys* 2012;39(3):1418–23
9. Gevaert T, Verellen D, Tournel K, Linthout N, Bral S, Engels B, et al. Setup accuracy of the Novalis ExacTrac 6DOF system for frameless radiosurgery. *Int J Radiat Oncol Biol Phys* 2012;82(5):1627–35
10. Almeida TVR, Junior ALC, Piedade PA, Da Silva CM, Marins P, Almeida CM, et al. Analysis of translational errors in frame-based and frameless cranial radiosurgery using an anthropomorphic phantom. *Radiol Bras* 2016;49(2):98–103
11. Spitzer M, Wildenhain J, Rappsilber J, Tyers M. Box-PlotR: A web tool for generation of box plots. *Nat Methods* 2014;11(2):121–2
12. Lewis BC, Snyder WJ, Kim S, Kim T. Monitoring frequency of intra-fraction patient motion using the ExacTrac system for LINAC-based SRS treatments. *J Appl Clin Med Phys* 2018;19(3):58–63

13. Oh SA, Park JW, Yea JW, Kim SK. Evaluations of the setup discrepancy between BrainLAB 6D ExacTrac and cone-beam computed tomography used with the imaging guidance system Novalis-Tx for intracranial stereotactic radiosurgery. *PLoS ONE* 2017;12(5):e0177798
14. Korytko T, Radvovoyevitch T, Colussi V, Wessels BW, Pillai K, Maciunas RJ, et al. 12 Gy gamma knife radiosurgical volume is a predictor for radiation necrosis in non-AVM intracranial tumors. *Int J Radiat Oncol Biol Phys* 2006;64(2):419–24
15. Minniti G, Clarke E, Lanzetta G, Osti MF, Trasimeni G, Bozzao A, et al. Stereotactic radiosurgery for brain metastases: Analysis of outcome and risk of brain radionecrosis. *Radiat Oncol* 2011;6:48
16. Hoogeman MS, Nuyttens JJ, Levendag PC, Heijmen BJM. Time dependence of intrafraction patient motion assessed by repeat stereoscopic imaging. *Int J Radiat Oncol Biol Phys* 2008;70(2):609–18
17. Jin JY, Ryu S, Faber K, Mikkelsen T, Chen Q, Li S, et al. 2D/3D image fusion for accurate target localization and evaluation of a mask based stereotactic system in fractionated stereotactic radiotherapy of cranial lesions. *Med Phys* 2006;33(12):4557–66
18. Zollner B, Heinz C, Pitzler S, Manapov F, Kantz S, Rottler MC, et al. Stereoscopic x-ray imaging, cone beam CT, and couch positioning in stereotactic radiotherapy of intracranial tumors: Preliminary results from a cross-modality pilot installation. *Radiat Oncol* 2016;11(1):158
19. Verellen D, Soete G, Linthout N, Van Acker S, De Roover P, Vinh-Hung V, et al. Quality assurance of a system for improved target localization and patient set-up that combines real-time infrared tracking and stereoscopic x-ray imaging. *Radiother Oncol* 2003;67(1):129–41
20. Wurm RE, Erbel S, Schwenkert I, Gum F, Agaoglu D, Schild R, et al. Novalis frameless image-guided noninvasive radiosurgery: Initial experience. *Neurosurgery* 2008;62(5):A11–8
21. Jani SK, Weinstein G, Shah N, Volpp P, Glazebrook S, Pothilat J, et al. Performance of an ExacTrac image guidance system in mask-based cranial radiotherapy on a classic Novalis machine: A five-year experience. *Int J Radiat Oncol Biol Phys* 2010;78(3):S765–6
22. Kojima H, Takemura A, Kurokawa S, Ueda S, Noto K, Yokoyama H, et al. Evaluation of technical performance of optical surface imaging system using conventional and novel stereotactic radiosurgery algorithms. *J Appl Clin Med Phys* 2021;22(2):58–68
23. Ma J, Chang Z, Wang Z, Wu QJ, Kirkpatrick JP, Yin FF. ExacTrac x-ray 6 degree-of-freedom image-guidance for intracranial non-invasive stereotactic radiotherapy: Comparison with kilo-voltage cone-beam CT. *Radiother Oncol* 2009;93(3):602–8
24. Spadea MF, Tagaste B, Riboldi M, Preve E, Alterio D, Piperno G, et al. Intra-fraction setup variability: IR optical localization vs x-ray imaging in a hypofractionated patient population. *Radiat Oncol* 2011;6:38
25. Takakura T, Mizowaki T, Nakata M, Yano S, Fujimoto T, Miyabe Y, et al. The geometric accuracy of frameless stereotactic radiosurgery using a 6D robotic couch system. *Phys Med Biol* 2010;55(1):1–10
26. Tanyi JA, Kernan C, Kato CM, Marquez C, Laub W, Fuss M. Comparison of image-guidance modalities for cranial stereotactic radiosurgery (SRS) and radiotherapy (SRT). *Int J Radiat Oncol Biol Phys* 2011;81(2):S826–7.