

Scientific Paper

Optimizing Isocenter Accuracy in ExacTrac Dynamic®: Daily Verification and Quality Assurance for Reliable Patient Positioning

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Abstract

Introduction: Advances in teleradiotherapy, such as SRS and SBRT, have improved treatment by delivering higher doses in fewer sessions, reducing duration, and sparing healthy tissue. These techniques require precise patient positioning, achieved through systems like SGRT (surface tracking) and IGRT (X-ray imaging). The ExacTrac Dynamic system (Brainlab AG, Germany) combines both, offering submillimetric accuracy for cranial radiotherapy. This study evaluates its quality assurance (QA) protocols, focusing on calibration, accuracy, and clinical performance.

Background and Purpose: SRS and SBRT allow targeted treatment with minimal margins, reducing complications. Precise alignment is essential, particularly for cranial cases. The study assesses the QA processes of the ExacTrac Dynamic system and evaluates its accuracy and reliability.

Results: Daily logs revealed differences between Surface Tracking and X-ray imaging. X-ray was more reliable, especially for longitudinal translational deviations, while Surface Tracking was affected by thermal artifacts. Rotational deviations remained within tolerance, with the largest shifts in yaw. Histogram analysis showed skewed distributions, underscoring the importance of combining both methods and regular QA.

Conclusion: Regular QA and recalibration of the ExacTrac Dynamic system are essential to address discrepancies between SGRT and X-ray methods. X-ray offers greater precision, while Surface Tracking is prone to environmental artifacts. Combining SGRT and IGRT ensures accuracy but requires consistent QA to maintain treatment precision.

Keywords: Stereotactic Radiotherapy, Quality Assurance, Surface-Guided Radiotherapy (SGRT), Image-Guided Radiotherapy (IGRT), ExacTrac Dynamic System

Introduction

Over the past decade, teleradiotherapy has increasingly shifted towards a stereotactic approach, characterized by delivering fewer treatment fractions with a higher dose per fraction, thereby significantly reducing the overall treatment duration¹. Simultaneously, advancements in irradiation techniques have enabled the reduction of margins around the tumor without compromising target coverage. These improvements also help to spare healthy surrounding tissue, ultimately decreasing the risk of complications such as necrosis². The development of SRS (Stereotactic Radiosurgery) and SBRT (Stereotactic Body Radiotherapy) techniques necessitates tools for verifying patient positioning both before and during treatment³. SGRT (Surface-Guided Radiotherapy) systems monitor a patient's surface using images captured by cameras installed in the linac

bunker⁴. However, their primary limitation is the inability to verify internal anatomy. For areas where the movement of the PTV (Planned Target Volume) is not reflected on the surface, such as the prostate or colon, or for situations requiring more precise positioning like for cranial targets⁵, IGRT (Image-Guided Radiotherapy) systems offer a viable alternative. IGRT verifies the target position using X-ray images, allowing for the consideration of internal anatomy within the treated region. One of the IGRT systems available on the market is the ExacTrac Dynamic (Brainlab AG, Germany), with over 300 units in operation as of July 2024. This system combines a pair of X-ray detectors with a 4D camera that monitors the patient's surface, including additional thermal information. The ability to perform X-ray-based verifications with submillimetric precision for non-coplanar couch angles has made it particularly popular for cranial cases. This precision helps eliminate patient

movement caused by couch rotation and compensates for discrepancies between couch and gantry isocenters^{6,7}. To ensure the quality assurance of the system, a set of software tools and phantoms has been developed for calibration and subsequent verification of accuracy and stability. The first calibration that must be performed before clinical use of the system is the Thermal to 3D Camera Calibration. For the relative calibration between the thermal and surface cameras, a specially designed phantom is used. This phantom features a white plane with seven reflective spots that can be recognized by the surface camera. Simultaneously, the phantom is heated, with the same spots remaining colder than the rest of the surface, allowing the thermal camera to distinguish them as well. The next step is the Isocenter Calibration. To align the surface-based and X-ray-based isocenters, the System Calibration Phantom must be positioned at the treatment isocenter, often using lasers for accuracy⁸. The phantom's surface has identifiable edges for the surface camera, along with radiopaque markers arranged in a specific pattern. When X-ray images are acquired, these markers enable the system to determine the isocenter position accurately⁹. The same phantom is used for daily verifications, known as the Daily Check. This two-step process begins by verifying the phantom's position using data from the surface camera and X-ray detectors, and then comparing the results to ensure the deviation between the two measurements is less than 1 mm and 1 degree. If this step is successful, the system displays the shifts of the phantom relative to the treatment isocenter. These shifts can be sent to the linac couch, and once applied, the final position of the phantom can be verified using the same technique employed during calibration. The final calibration, which is optional but highly recommended by the vendor, is the Radiation-Isocenter Calibration. This process involves performing a Winston-Lutz test using a phantom equipped with a radiopaque sphere placed at the linac's radiation isocenter^{10,11}. The ExacTrac Dynamic system then acquires a pair of X-ray images of the phantom and identifies the sphere's position. The vector between this point and the isocenter determined during the Isocenter Calibration step is recorded and applied to all subsequent calculations performed by the software¹². The aim of this work is to investigate the QA (Quality Assurance) in the Brainlab ExacTrac Dynamic system and to conduct a comprehensive analysis of the data collected during its clinical use¹³.

Materials and Methods

ExacTrac Dynamic is a patient positioning device designed for use in a radiotherapy environment as an add-on system to standard linear accelerators. At our institution, the Brainlab ExacTrac Dynamic system (version 2.0) was integrated with the TrueBeam linear accelerator (Varian Medical Systems). One of the essential components of quality assurance (QA) for this system involves performing a Daily Check. During the Daily Check of the Brainlab ExacTrac Dynamic system, the following aspects are verified:

- The cross-calibration of the 3D Camera and the X-ray isocenter,
- The stability of the system's geometric setup, ensuring no changes have occurred,
- The alignment of the phantom's position with the saved isocenter coordinates¹⁴.

A System Calibration Phantom was employed for quality assurance. It was positioned at the isocenter of the linear accelerator, with the accelerator's laser system utilized for precise alignment. This publication investigates the discrepancies between the X-ray and Surface Camera coordinate systems. Specifically, it analyzes translational deviations (lateral, longitudinal, and vertical displacements) in millimeters and rotational deviations (pitch, roll, and yaw angles) in degrees. The statistical parameters of the measurements presented in this study were calculated using the following formulas:

- mean value

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i \quad (1)$$

- standard deviation

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \quad (2)$$

- skewness

$$\gamma = \frac{1}{N} \sum_{i=1}^N \left(\frac{x_i - \mu}{\sigma} \right)^3 \quad (3)$$

- kurtosis

$$\omega = \frac{1}{N} \sum_{i=1}^N \left(\frac{x_i - \mu}{\sigma} \right)^4 \quad (4)$$

where x_i is the value of the measurement and N is a total number of measurements^{15,16}.

Data Analysis and Results

Daily log files were exported from the ExacTrac Dynamic system for the period spanning November 2023 to July 2024 and subsequently analyzed in this study. **Table 1** presents the discrepancies between the X-ray and Surface Camera coordinates. To determine whether a significant difference exists in the shift detection between the X-ray and Surface Camera, a Wilcoxon signed-rank test was performed. The significance level (α) was set at 0.05 for rejecting the null hypothesis.

Figure 1 illustrates the exported daily check data for translational deviations in the lateral and longitudinal directions. As anticipated, all displacements were observed to be within the tolerance limit of 1 mm.

Figure 2 displays the exported daily check data for rotational deviations in the pitch and roll directions. The deviations were also within the tolerance limit of 1 degree, with the largest observed displacement being 0.06 degrees for both pitch and roll.

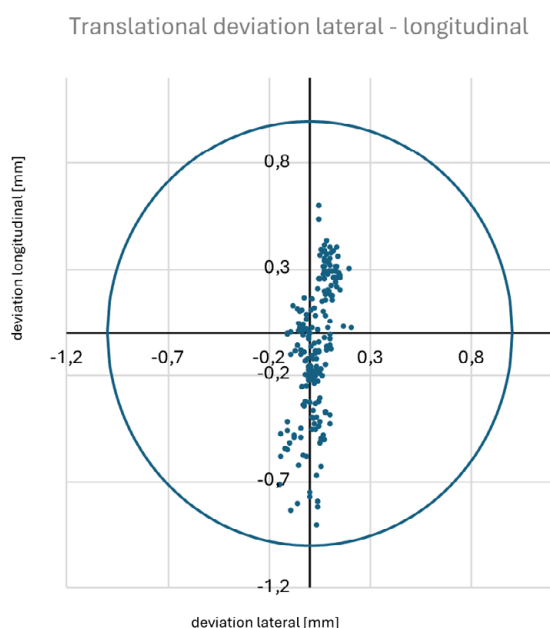


Figure 1. All exported daily check data for translational deviation in lateral and longitudinal directions.

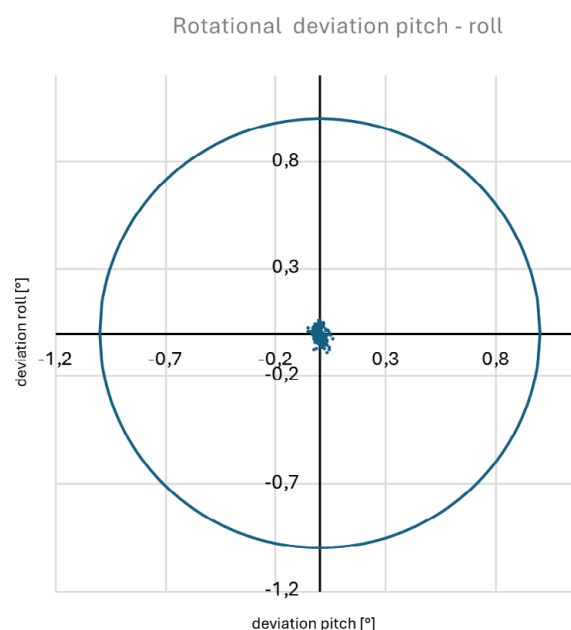


Figure 2. All exported daily check data for rotational deviation in pitch and roll directions.

Table 1. Differences between X-ray and Surface Camera coordinates in all 6 directions.

	Translational deviation [mm]			Rotational deviation [°]		
	Lateral	Longitudinal	Vertical	Pitch	Roll	Yaw
mean	0.03	-0.07	-0.07	0	0	-0.03
min	-0.15	-0.91	-0.48	0.05	0.09	0.12
max	0.21	0.60	0.75	0.06	0.06	0.08
SD	0.07	0.32	0.22	0.02	0.03	0.04
skewness	-0.28	-0.38	0.52	0.15	-0.28	0.33
kurtosis	-0.10	-0.45	0.80	0.31	-0.65	-0.50
*p value	<0.001**	0.011**	<0.001**	0.09	0.15	<0.001**

* The p-value was calculated using the Wilcoxon signed-rank test

** The p-value has a statistical significance of difference ($p < 0.05$)

More specifically, the largest translational difference between the X-ray and Surface Camera coordinates was observed in the lateral direction (0.03 ± 0.07 mm), followed by the vertical (-0.07 ± 0.22 mm) and longitudinal (-0.07 ± 0.32 mm) directions.

For rotational deviations, identical differences were recorded in the pitch and roll directions, amounting to ($0 \pm 0.02^\circ$) and ($0 \pm 0.03^\circ$), respectively. The rotational difference in the yaw direction was measured at ($-0.03 \pm 0.04^\circ$).

Wilcoxon signed-rank tests indicated that the differences between X-ray and Surface Camera coordinates were statistically significant ($p < 0.05$) for all translational directions and for the rotational deviation in the yaw direction.

Histogram Analysis for Translational and Rotational Deviations

As the next step in the analysis, histograms were generated to visualize the distributions of translational and rotational deviations (Figure 3). To better understand the properties of

these distributions, kurtosis and skewness were calculated as measures of asymmetry and shape.

Skewness describes the asymmetry of a distribution relative to its mean. A positive skewness value indicates a longer tail on the right side of the distribution, whereas a negative skewness value signifies a longer tail on the left side. This metric is useful for identifying the shape and potential outliers within the dataset.

Kurtosis, on the other hand, quantifies the “tailedness” of a probability distribution. It measures the propensity of a distribution to produce extreme values compared to a normal distribution. Positive kurtosis reflects heavier tails and a more sharply peaked distribution, while negative kurtosis indicates lighter tails and a flatter distribution. This metric provides insights into the frequency and impact of outliers in the dataset.

Together, these statistical measures offer a detailed understanding of the dataset’s characteristics, including its deviation from normality and the behavior of outliers.

The calculated skewness values for translational deviations in the lateral and longitudinal directions were -0.28 and -0.38, respectively, both indicating left-skewed distributions, as shown in the histograms in Figure 3a.

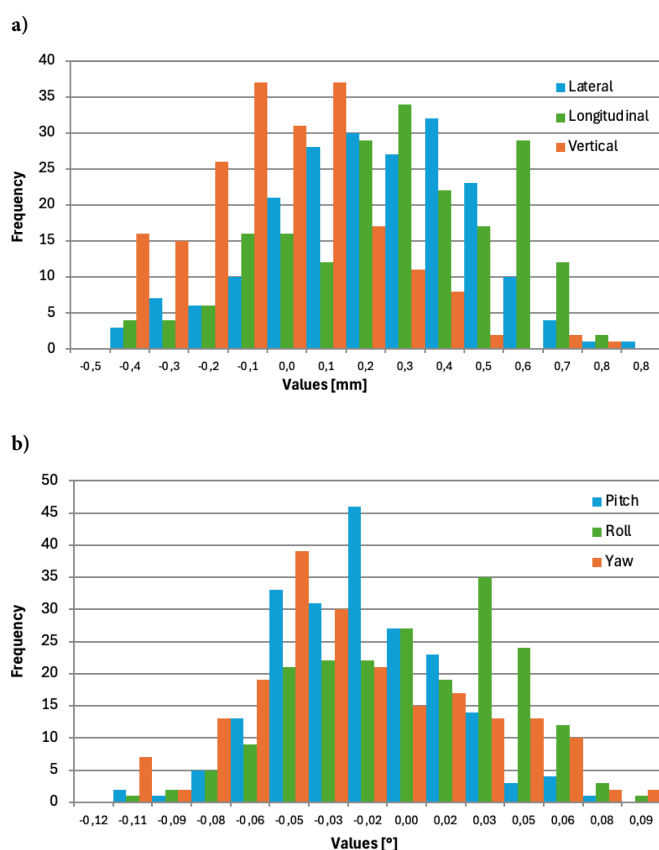


Figure 3. Histograms for the deviation of phantom 3D camera view and X-Ray system view. a) Histogram for the translation direction. b) Histogram for the rotation direction.

For rotational deviations in the pitch direction (Figure 3b), the skewness also reflects left skewness, with a value of -0.28. The pronounced asymmetry observed in the translational lateral direction may be attributed to individual variations among personnel performing the daily measurements, as well as the inherent challenges in achieving precise phantom positioning along this axis.

In contrast, right skewness, representing the highest degree of asymmetry, was observed in the translational vertical deviation, with a skewness value of 0.52.

Analysis of Shifts for Head Tumors

The ExacTrac Dynamic system is designed to automatically interrupt the beam delivery if deviations between the current and reference surfaces exceed predefined tolerance levels^{14,17}. For head tumors, the Surface Tracking tolerance is set to 1.5 mm and 1.5 degrees, while for X-ray imaging, stricter tolerances of 0.5 mm and 0.5 degrees are applied in each direction. The stricter tolerance for X-ray imaging is used to ensure highly precise patient positioning, which is crucial for effective and safe radiation therapy. If these tolerances are exceeded, the system initiates X-ray imaging to verify and correct the patient's position.

Throughout the treatment process, the ExacTrac Dynamic system continuously monitors the patient's position at specific therapeutic beam delivery points. Positional data for each

fraction of treatment under both Surface Tracking and X-ray imaging were automatically recorded in the system's log files.

For this study, treatment log files were exported for 10 patients. The recorded shifts in Surface Tracking and X-ray imaging were analyzed for cases with identical numbers of monitor units. To determine whether a significant difference exists in shift detection between Surface Tracking and X-ray imaging, a Wilcoxon signed-rank test was performed. The significance level (α) was set at 0.05 for rejecting the null hypothesis.

Analysis of Shift Detection and Verification

The Wilcoxon signed-rank tests revealed significant differences in shift detection between Surface Tracking and X-ray verification in the pitch direction ($P < 0.05$).

In the histogram (Figure 4a), the elongated left tail in the vertical direction, and to a lesser extent in the lateral direction, indicates left-skewed distributions. Additionally, the data tend to cluster more frequently within the range of 0 to 0.2 mm. For rotational deviations, the ExacTrac system detected notably larger shifts in the roll direction, as shown in Figure 4b. In contrast, right skewness was observed in the pitch and yaw directions.

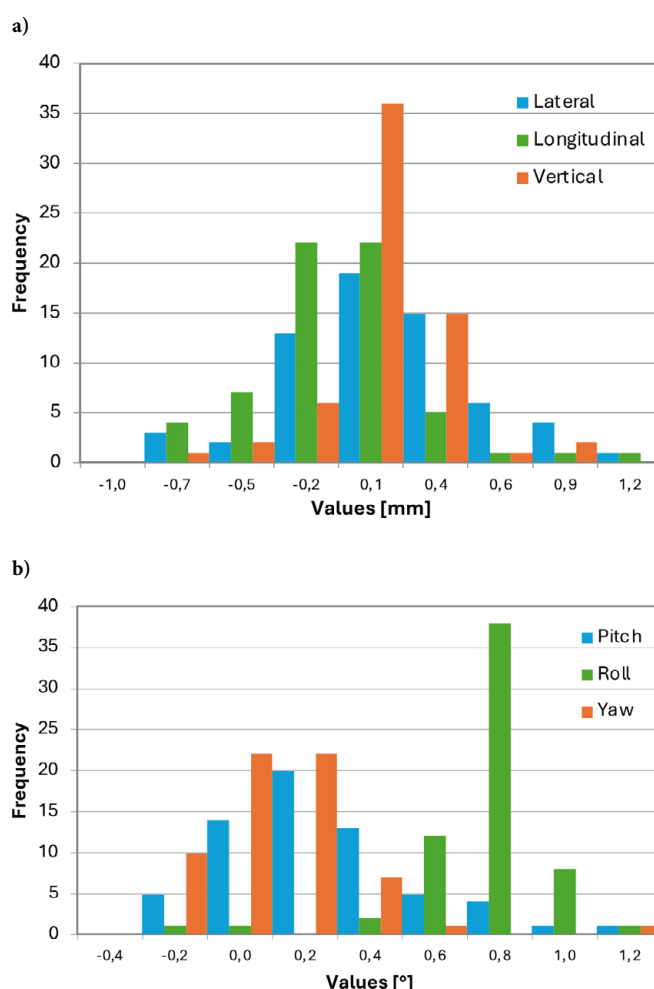


Figure 4. Histograms of deviations recorded by Surface Tracking. a) Histogram for the translation direction. b) Histogram for the rotation direction.

In **Figure 5**, which visualizes shifts recorded by X-ray, a right-skewed distribution is evident in the lateral and longitudinal directions, while an elongated left tail dominates the vertical direction. For rotational deviations, right skewness was consistently noted in the pitch, roll, and yaw directions.

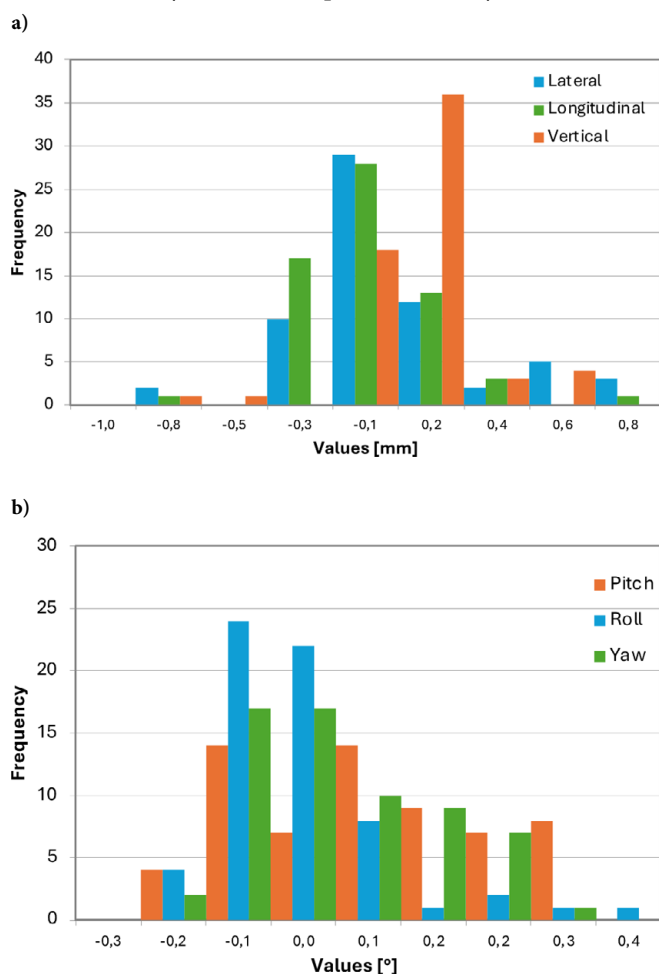


Figure 5. Histograms of deviations recorded by X-Ray verification. a) Histogram for the translation direction. b) Histogram for the rotation direction.

These findings emphasize the importance of verifying patient positioning with X-ray imaging during treatment to ensure accuracy.

Shift Analysis

The differences in shifts detected by ExacTrac Dynamic are summarized in **Table 2**.

For Surface Tracking, the largest translational deviation was observed in the longitudinal direction (0.04 ± 0.27 mm), followed by the lateral (0.02 ± 0.33 mm) and vertical (-0.01 ± 0.27 mm) directions. Regarding rotational deviations, the largest shift was recorded in the yaw direction ($0.05 \pm 0.21^\circ$), with smaller deviations in roll ($-0.01 \pm 0.17^\circ$) and pitch ($-0.01 \pm 0.14^\circ$).

For X-ray verification, the largest average translational deviation was also observed in the longitudinal direction (0.04 ± 0.29 mm), followed by the lateral (0.03 ± 0.16 mm) and vertical (-0.01 ± 0.23 mm) directions. The highest rotational deviation was detected in the yaw direction ($0.03 \pm 0.15^\circ$), with smaller deviations in pitch ($0.02 \pm 0.15^\circ$) and roll ($0.02 \pm 0.06^\circ$).

The average translational and rotational deviations for both methods were less than 1 mm and 1° , respectively. These results underscore the importance of real-time motion monitoring and position correction to ensure precise target irradiation while minimizing exposure to surrounding healthy tissues.

Conclusions

This study revealed that there is a need to perform a daily verification of the agreement between two methods of isocenter definition in ExacTrac Dynamic – surface-based and X-ray-based, in a form of built-in Daily Check workflow. As the components of the system responsible for both techniques are

Table 2 Differences of shifts detected by ExacTrac Dynamic for Surface Tracking and X-Ray in all 6 directions.

Surface Tracking	Translational deviation [mm]			Rotational deviation [°]		
	Lateral	Longitudinal	Vertical	Pitch	Roll	Yaw
mean	0.02	0.04	-0.01	-0.01	-0.01	0.05
min	-0.66	-0.74	-0.99	-0.26	-0.81	-0.31
max	0.67	1.18	0.88	0.41	0.29	1.03
SD	0.27	0.33	0.27	0.14	0.17	0.21
skewness	-0.03	0.63	-0.16	0.73	-2.5	1.63
kurtosis	0.35	1.86	4.55	0.57	10.31	6.16
X-Ray verification						
mean	0.03	0.04	-0.01	0.02	0.02	0.03
min	-0.39	-0.93	-0.99	-0.24	-0.09	-0.24
max	0.40	1.03	0.60	0.54	0.18	0.29
SD	0.16	0.29	0.23	0.15	0.06	0.15
skewness	0.54	0.22	-1.10	1.55	0.53	0.05
kurtosis	0.87	2.94	6.74	3.36	-0.44	-1.06
*p value	0.55	0.96	0.70	0.03**	0.28	0.31

* The p-value was calculated using the Wilcoxon signed-rank test

** The p-value has a statistical significance of difference ($p < 0.05$)

separated from each other (4D camera unit is physically not attached to the X-ray tubes and detectors), the drifts between results can be observed. The 4D camera or X-ray detectors may lower oneself under one's own weight. That agrees with observed results as the translation movement, especially in vertical and longitudinal directions, is much more prominent than detected rotations. To overcome that issue, a regular recalibration of the system is recommended when the differences between both isocenters approach the values of 1 mm and 1 degree. When comparing detected values of translation and rotation shifts by 4D Camera and X-ray system, the Surface-based results tend to indicate larger discrepancies from the ideal position than the X-ray component, which is more reliable and less susceptible to intrafractional drifts, caused often by the thermal information. The temperature of the Surface Tracking Area can change during monitoring, which has an impact on the displayed values. To minimize the influence of temperature drifts that may cause the observed discrepancies, the Surface-based shift values are updated after every X-ray Verification which becomes the reference for the 4D Camera until the next images are taken. The data clearly confirm IGRT as the gold standard for patient positioning, due to its ability to directly image internal anatomy with high spatial accuracy. This direct visualization reduces uncertainties caused by patient surface changes or external factors. On the other hand, SGRT tracks external patient surfaces using optical imaging, which is more susceptible to fluctuations caused by lighting

conditions, patient movement, skin deformation, and device calibration issues. These factors can introduce artifacts and reduce precision, as reflected in our results. Despite these limitations, SGRT provides valuable continuous, non-ionizing real-time monitoring that complements the intermittent but highly accurate IGRT. The combination of both techniques leverages the strengths of each: IGRT ensures precise anatomical alignment, while SGRT enables motion tracking during treatment delivery. To ensure optimal performance, rigorous and regular quality assurance and calibration of both systems are essential. This integrated approach ultimately enhances treatment accuracy and patient safety by balancing precision and continuous monitoring. The use of specialized phantoms and dedicated software tools is crucial in each stage of the quality assurance process to ensure the system's accuracy and reliability. These devices enable precise calibration by providing known reference points that can be consistently recognized by both the surface and thermal cameras, as well as by the X-ray imaging system. Without such carefully designed equipment, it would be impossible to verify alignment and stability with the sub-millimeter and sub-degree precision required for effective patient treatment. Moreover, regular use of these phantoms in daily checks allows early detection of system deviations or drifts, ensuring timely corrections before clinical application. Thus, the integration of advanced hardware and software QA tools is fundamental to maintaining the high standards necessary for safe and effective radiation therapy.

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