

Implementation and Application of the IORT INTRABEAM 600 System – Commissioning Measurements and Independent Treatment Verification

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Abstract

Introduction: Intraoperative radiotherapy (IORT) delivers a single high-dose radiation fraction directly to the tumor or tumor bed during surgery, minimizing exposure to healthy tissue. The INTRABEAM 600 system, with its compact design and low-energy X-rays, requires thorough commissioning and quality assurance. This study performs dosimetric measurements, establishes an independent verification method, and compares Calibration v4.0 and TARGIT approaches to ensure accurate, safe, and reliable IORT delivery, supporting improved clinical outcomes.

Materials and Methods: The INTRABEAM 600 system delivers low-energy X-rays via a XRS generator for precise intraoperative radiotherapy. Commissioning involved depth dose rate measurements in a water phantom using ionization chambers, with probe tip positioned along X, Y, and Z axes. Dose rates were determined using Calibration v4.0 and TARGIT methods, correlated via a conversion function. QA checks included PAICH output, IRM baseline, and isotropy verification, ensuring accurate, reproducible treatment delivery.

Results: Dynamic offset analysis showed minimal deviations, confirming accurate beam targeting. The Output Check confirmed stable system performance. Depth dose rate curve measurements revealed a mean difference of $-1.3 \pm 1\%$ from certification data. Treatment time calculations using spherical applicators showed minor differences between INTRABEAM600 and radiance, with the largest at $-1.9 \pm 1.1\%$ for the 20 mm applicator. TARGIT results were similar, with the largest differences at $-1.8 \pm 0.6\%$ for the 15 mm and 20 mm applicators.

Conclusion: Comprehensive commissioning and QA confirmed that the INTRABEAM 600 system is stable, precise, and clinically reliable. Dynamic offsets showed minimal deviations, verifying correct beam alignment, while Output Check tests confirmed XRS generator stability. Depth dose rate measurements agreed closely with certification data $-1.3 \pm 1.0\%$. Treatment time comparisons using Calibration v4.0 and TARGIT showed minor discrepancies, largest for small applicators (15–20 mm). Independent verification and radiance simulations support accurate dose delivery.

Keywords: IORT, IORT dosimetry, TARGIT, V4.0, Isotropy, Independent Verification

Introduction

Intraoperative radiotherapy (IORT) is an advanced radiation technique that delivers a single, high-dose fraction of radiation directly to the tumor or tumor bed during surgery. This approach minimizes radiation exposure to surrounding healthy tissues and reduces overall treatment time compared to conventional external beam radiotherapy (EBRT). Among various IORT systems, the INTRABEAM 600 system has gained prominence due to its compact design, ease of integration into the surgical workflow, and effective dose delivery characteristics using low-energy x-rays photons¹. The implementation of a IORT system, such as the INTRABEAM 600, requires commissioning and quality assurance (QA) to ensure

patient safety and treatment efficacy. Commissioning involves detailed dosimetric measurements, beam characterization, and verification of dose distributions using appropriate phantoms and detectors^{2,3}. These measurements establish data for clinical use and allow for comparison with treatment planning simulation systems, including the Radiance system and the INTRABEAM 600 system. An essential aspect of clinical implementation is the creation of an independent verification system to cross-check treatment parameters, such as exposure time, alongside the comparison of the measured XRS (X-ray generator) output value with the calculated XRS output value. Independent dose calculations help identify potential discrepancies in generated values, ensuring accurate and reproducible treatment delivery. The main research question of this study

is: Can an independent verification approach, based on depth dose rate measurements and comparison of Calibration v4.0 and TARGIT methods, provide reliable confirmation of the INTRABEAM 600 system's treatment parameters?

Accordingly, the objectives of this work are to perform comprehensive commissioning measurements for the INTRABEAM 600 system, including the determination of the XRS Depth Dose Rate Curve and the assessment of its isotropy function. Furthermore, the study aims to establish an independent treatment verification method capable of cross-checking calculated and measured treatment times. The performance of the Calibration v4.0 and TARGIT methods in clinical dosimetry is compared to evaluate their accuracy and reliability. Finally, the potential clinical significance of these procedures is assessed in the context of ensuring precise and safe delivery of intraoperative radiotherapy. IORT has been explored as an adjunctive treatment modality to improve local tumor control and overall survival by delivering a concentrated dose of radiation immediately following tumor resection^{4,5}. This approach reduces the likelihood of tumor recurrence and may improve patient outcomes compared to conventional post-operative radiation alone⁶. By addressing these objectives, the study aims to strengthen the reliability of IORT treatments and contribute to the broader field of intraoperative radiation oncology through improved QA and verification practices.

Materials and Methods

INTRABEAM 600

The INTRABEAM 600 (Carl Zeiss Meditec AG) system's core component is the miniature X-ray generator, which functions as a linear accelerator emitting 50 kV low energy X-ray photons. The XRS generator features a 10 cm long, 3.2 mm diameter X-ray probe designed to emit low-energy radiation at high doses. This is accomplished by accelerating electrons along the probe with a maximum acceleration voltage of 50 kV. Upon reaching the tip of the probe, the electrons collide with the target material, resulting in the emission of X-ray radiation. The energy of the emitted X-rays is approximately 21 kV or lower. Due to the low energy of X-rays in soft tissues, the radiation dose attenuates rapidly ($\sim 1/r^3$). As a result, the treated lesion serves as a protective

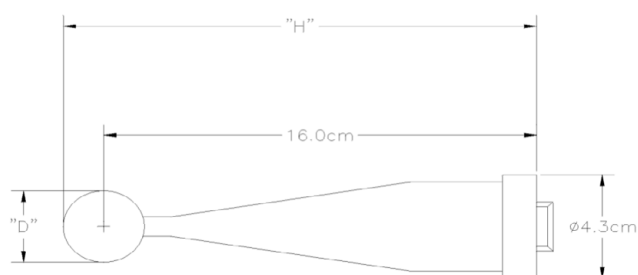


Figure 1. Schematic illustration of a spherical applicator⁸.

Table 1. Dimensions of spherical applicators.

Spherical applicators		
Applicator size [cm]	Diameter - D [mm]	Length - H [mm]
1.5	12	167.5
2	20	170
2.5	25	172.5
3	30	175
3.5	35	177.5
4	40	180
4.5	45	182.5
5	50	185

barrier, effectively reducing radiation exposure to the surrounding healthy tissue⁷.

Various applicators can be attached to the tip of the XRS generator probe to accurately deliver radiation to a targeted lesion for localized treatment or to be positioned within the resection cavity following tumor removal. At our hospital, spherical applicators (Figure 1) are available in the following sizes: 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, and 50 mm (Table 1)⁸.

Quality Assurance

Before each treatment, a two-stage quality control check ensures that all parameters such as isotropy, internal radiation monitor and dose output do not exceed the tolerances defined during calibration. Within the photo diode array (PDA), five orthogonally positioned diodes measure the radiation emitted by the XRS. This test is designed to verify the isotropy of the beam, ensuring a spherical emission pattern. The PAICH is used to assess radiation output. An ion chamber is securely mounted on the probe adjuster, positioning its window directly above the XRS tip. This test also includes verification of the internal IRM. Additionally, temperature sensors are integrated within the PAICH, while pressure sensors are located inside the Control Console 600^{7,9}.

Water phantom

The water phantom is utilized to measure the depth dose rate curve and evaluate the isotropy of the XRS generator within the INTRABEAM 600 system, ensuring that the recorded values are consistent with the expected range⁹. The depth dose rate curve characterizes the dose rate [Gy/min] as a function of penetration depth [mm] in water for the X-ray generator at 40 kV and 50 kV. The water phantom consists of a radiation-shielded water tank designed to facilitate the precise positioning of the XRS generator tip. The tank is equipped with two plastic holders for the ionization chamber, ensuring accurate measurements during testing. The probe tip can be accurately adjusted along the X, Y, and Z axes using micrometric screws to align it with the measurement chambers. All dosimetric measurements were performed using the INTRABEAM 600 software.

Ionization chamber TN23342, TN34013

The TN23342 ionization chamber has an active volume of approximately 0.6 cm^3 and exhibits high sensitivity, making it particularly suitable for measurements of low to medium energy photon beams. In contrast, the TN34013, with a smaller active volume of about 0.3 cm^3 , is optimized for dosimetry of medium to high-energy photon and electron beams commonly used in clinical therapy. Chamber factors such as N_k , k_Q , and $k_{Ka \rightarrow Dw}$ were obtained from calibration certificates. For the TN34013 chamber, the values are $Nk = 5.348 \cdot 10^9 \text{ Gy/C}$, $k_Q = 1$, and $k_{Ka \rightarrow Dw} = 1.045$, whereas for the TN23342 chamber, they are $Nk = 1.608 \cdot 10^9 \text{ Gy/C}$, $k_Q = 1$.

Radiance

Radiance is a software system designed for treatment planning simulation and analysis of radiation therapy delivered using devices adapted for IORT. Key parameters in IORT include the applicator's geometry (such as bevel angle and diameter), its orientation and positioning relative to the patient, as well as the energy of the accelerator¹⁰. The dose distribution is determined by simulating the interaction of electrons or photons with tissues. This process employs advanced algorithms, including Pencil Beam, Monte Carlo, Dose Painting, and Hybrid Monte Carlo, which calculate the dose distribution based on density data from the patient's CT scans or measurements in water¹¹.

The essential steps for comprehensive treatment planning using radiance are outlined below.

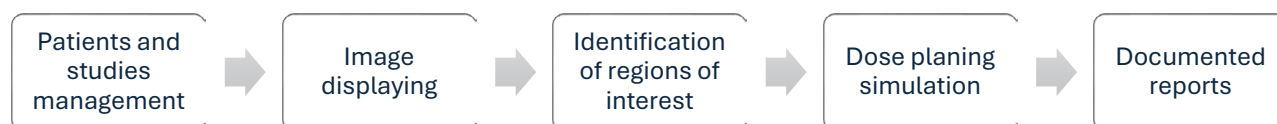


Figure 2. Steps of planning in the radiance software¹⁰.

Probe Tip Positioning in X, Y and Z Directions

To measure the depth dose rate curve, the following steps should be performed: mount the XRS system and place the ionization chamber (PTW TN34013) in the water phantom, precisely align the probe tip with the center of the ionization chamber along the X, Y, and Z axes, record the dose rate at specific positions along the Z-axis, and compare the measured depth dose rate curve with the calibrated reference values. The precise positioning of the probe tip is critical to ensure accurate dose measurements. The objective is to align the probe tip so that the housing of the depth dose measurement chamber makes contact with the center of the ionization chamber measurement window. In this context, “contact” refers to a slight touch between the probe tip and the measurement chamber, without exerting any measurable force^{7,9}. To verify that the maximum current intensity value was reliably identified, the repeatability of the chamber positioning was evaluated through multiple trials.

Positioning in the Z direction is carried out using a control knob with an indicator. The indicator's zero posi-

tion is set at the highest point. It displays the displacement in 1 mm increments with two decimal places. To accurately position the probe tip in the Z direction, it should be gradually lowered while monitoring the gap between the probe tip and the measurement chamber. The correct Z position is achieved the moment the gap is no longer visible. Once the probe tip makes contact with the measurement chamber, no further downward adjustment of the micrometer z-screw should be made. Another method for positioning the probe is based on current measurement. The exact position of the probe tip is reached at the point where the current intensity value is at its maximum. After completing the positioning process, the displayed Z position from the positioning system must be recorded. The recorded Z position during the measurements, denoted as Z_1 [mm], is essential for subsequent calculations. In this study, the probe was positioned using both methods described above to ensure the reliability and accuracy of the measurements. The subsequent section of this publication provides a detailed description of the variable Z_1 , which is used in Equation (8).

Depth Dose Rate Curve Measurement and Applied Formulas

The ionization chamber current was measured for distances in the range of $3 \text{ mm} < z < 45 \text{ mm}$ with a step size of $\Delta z = 1 \text{ mm}$, using an XRS tube current of $I = 40 \text{ }\mu\text{A}$ and a tube voltage of $U = 50 \text{ kV}$. The measured temperature T and ambient air pressure p in the immediate vicinity of the water phantom were

used to normalize the chamber current $I(z)$ to reference conditions, under which the ionization chamber was calibrated by PTW (typically $p_0 = 1013.2 \text{ hPa}$ and $T_0 = 295.2 \text{ K}$). This normalization can be expressed by the following equation:

$$I_{T,p}(z) = I(z) \cdot \frac{T}{T_0} \cdot \frac{p_0}{p} \quad (1)$$

This ensures that all measured values are corrected for environmental variations, allowing for accurate and reproducible dose measurements^{7,9}.

The TARGIT Method

The water phantom designed for measuring the low-energy X-ray generator serves as a quality control accessory for the user. Additionally, it enables precise positioning of the XRS radiation generator relative to the PTW TN34013 ionization chamber, which features a smaller entrance window. The algorithm used to calculate the absorbed dose in water was developed and adapted in collaboration between ZEISS and the TARGIT Physics Group.

$$\dot{D}w(z) \left[\frac{\text{Gy}}{\text{min}} \right] = IT, p(z) [A] \cdot kQ \cdot NS \left[\frac{\text{R}}{\text{C}} \right] \cdot f \left[\frac{\text{Gy}}{\text{R}} \right] \cdot 60 \left[\frac{\text{s}}{\text{min}} \right] \quad (2)$$

The conversion of corrected exposure values to the absolute absorbed dose rate in water $\dot{D}w(z)$ [Gy/min] at various water depths is performed through the calibration of the TN23342 ionization chamber in a water phantom, using the exposure calibration factor N_s [R/C]. To translate the measured exposure values into absorbed dose values in water, the X ray to gray conversion factor must be applied^{7,9,12}.

Calibration Method v4.0

This measurement method is based on the use of the PTW TN34013 ionization chamber, calibrated for air kerma. The conversion of the corrected ionization chamber current at various water depths (**Equation 1**) into the absolute absorbed dose rate in water $\dot{D}w(z)$ [Gy/min] is performed through the calibration of the TN34013 chamber using the air kerma calibration factor N_k [Gy/C].

$$\dot{D}w(z) \left[\frac{\text{Gy}}{\text{min}} \right] = IT, p(z) [A] \cdot kQ \cdot NK \left[\frac{\text{Gy}}{\text{C}} \right] \cdot k_{Ka \rightarrow Dw} \cdot 60 \left[\frac{\text{s}}{\text{min}} \right] \quad (3)$$

To translate the measured air kerma values into absorbed dose values in water, the air kerma to water absorbed dose conversion factor $k_{Ka \rightarrow Dw}$ is applied. This factor is determined during the chamber calibration process by the manufacturer (PTW).

Correlation between Calibration v4.0 and TARGIT method

The correlation between the depth dose rate curve measured by Calibration v4.0 and TARGIT method is defined by the following formula:

$$\dot{D}w(z)^{\text{TARGIT}} = f'(z) \cdot \dot{D}w(z)^{\text{Calibration v4.0}} \quad (4)$$

$f'(z)$ stands for the TARGIT to Calibration v4.0 method conversion function. It has a standard error of max. 5.1%. The values for the conversion function itself can be taken from the calibration certificate of the XRS^{7,9}.

Determination of PAICH output and IRM base line value

Before or immediately after the depth dose rate curve measurement, a factory calibrated PAICH unit and an ionization chamber, both subject to routine test equipment monitoring, are used to evaluate the PAICH dose output of the customer's XRS generator at tube voltages of 40 kV and 50 kV with a tube current of 40 μA . Furthermore, the corresponding IRM rates are recorded. The factory baseline PAICH output is determined using the following equation:

$$\dot{D}(\text{PAICH})_{\text{Base}} \left[\frac{\text{Gy}}{\text{min}} \right] = IT, p(\text{PAICH}) [A] \cdot kQ \cdot NK \left[\frac{\text{Gy}}{\text{C}} \right] \cdot 60 \left[\frac{\text{s}}{\text{min}} \right] \quad (5)$$

where:

- $I_{T,p}^{(\text{PAICH})}$ represents the ion current measured within the PAICH ionization chamber, corrected for the current tem-

perature T and air pressure p . Temperature and pressure corrections are made using a calibrated temperature sensor embedded in the PAICH and a calibrated barometer located in the Control Console 600.

- The calibration factor N_k and the beam quality correction factor k_Q are both derived from the Air Kerma Calibration Certificate of the PAICH factory ionization chamber.

After the successful completion of the QA procedure, the absolute dose output in water, represented by the depth dose rate curve for treatment planning, is determined based on the following equation:

$$\dot{D}_{W(z)\text{Actual}} \left[\frac{\text{Gy}}{\text{min}} \right] \{XRS\} = \dot{D}_{W(z)\text{Base}} \left[\frac{\text{Gy}}{\text{min}} \right] \{XRS\} n \frac{\dot{D}_{(\text{PAICH})\text{Actual}} \left[\frac{\text{Gy}}{\text{min}} \right]}{\dot{D}_{(\text{PAICH})\text{Base}} \left[\frac{\text{Gy}}{\text{min}} \right]} \quad (6)$$

This allows the software to determine the dose output, $\dot{D}_{W(z)\text{Treat}}$ [Gy/min], for each distance from the XRS isocenter or, alternatively, from the applicator surface through coordinate transformation. Additionally, the software calculates the total treatment duration t [min] required to deliver the prescribed dose at a specific treatment depth z_0 . The total number of IRM counts corresponding to the intended treatment dose is derived from the pre-calculated treatment time and the actual IRM rate [counts/s] measured during the QA procedure at a given tube voltage and current. Unlike a fixed preset time, the actual treatment duration defined as the period during which the XRS emits radiation can dynamically adjust, increasing or decreasing based on the real-time output of the XRS^{12,13}.

Before performing depth dose rate curve measurements, it is essential to determine the minimum distance r_1 between the probe tip and the ionization chamber at which measurements can be conducted. This distance is calculated using the following equation:

$$r_1 = d_H + d_A + d_{IC} \quad (7)$$

where:

- d_H represents the thickness of the measurement chamber wall,
- d_A denotes the gap between the upper part of the ionization chamber housing and the inner side of the measurement chamber wall (a constant value of 0.5 mm),
- d_{IC} is the reference distance from the ionization chamber to the upper part of its housing, as specified in the PTW calibration certificate.

To acquire the depth dose rate curve, the probe tip was systematically repositioned further (upward) from the optimal position Z_i in 1 mm increments. Each adjustment within the positioning system was recorded, and the new distance r_1 was determined using the following formula:

$$r_1 = r_i (Z_1 + Z_i) \quad (8)$$

Results

Table 2 presents the mean values of dynamic offsets X and Y along with their standard deviations. **Figure 3** illustrates the results of the dynamic offsets quality control. Analysis of **Table 2** and **Figure 3** indicates that the deviations from the center (0,0) point, representing the applied corrections, are minimal. This test confirms that the beam bending alignment has been performed correctly, ensuring precise targeting of the designated area.

Table 2. Mean values and standard deviations of X [mm] and Y [mm] from dynamic offsets quality control tests.

Dynamic Offsets [mm]	Mean [mm]	Standard deviation [mm]
X	-0.032	0.024
Y	-0.059	0.014

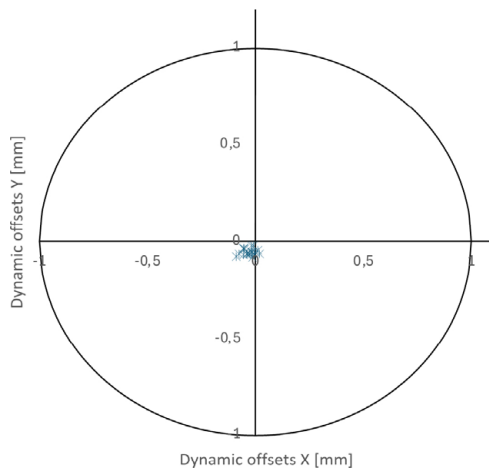


Figure 3. Measurement data from the dynamic offsets test.

The next stage of quality control involves performing the Output Check test. This test assesses the dose rate stability of the XRS generator using an ion chamber and an electrometer. The software compares the measured dose rate with the expected reference value derived from calibration data. The output value from the obtained XRS generator certificate is 3.781 [Gy/min]. **Table 3** presents the mean output value along with its standard deviation, measured during quality control tests.

Table 3. Mean value and standard deviation of the Output Value [Gy/min] from the Output Check test.

QA Output Check	Mean	Standard deviation
Output Value [Gy/min]	3.823	0.027

Quality control, including isotropy, internal radiation monitoring, and dose output, is based on the analysis of data collected over a six-month period.

Depth dose rate curve measurements

Table 4 presents the values used to calculate the distance between the probe tip and the ionization chamber. In our case, the calculated value of the parameter r_1 is 1.655 mm.

Table 4. Data values used for the calculation of r_1 .

Parameter	Value [mm]
d_H	0.9
d_A	0.5
d_{IC}	0.255

The ionization chamber current was measured for distances in the range of $3 \text{ mm} < z < 45 \text{ mm}$ with a step size of $\Delta z = 1 \text{ mm}$, using an XRS tube current of $I = 40 \mu\text{A}$ and a tube voltage of $U = 50 \text{ kV}$. For each ionization chamber depth within the range of 3 to 45 mm, with an increment of $\Delta z = 1 \text{ mm}$, the position Z_i was calculated according to **Equation (8)**.

Subsequently, charge measurements $Q[C]$ were performed at each depth for 60 seconds, and the dose rate $\dot{D}_w(r)$ [Gy/min] was calculated. The dose rate as a function of depth r was calculated using the following equation:

$$\dot{D}_w(r) \left[\frac{\text{Gy}}{\text{min}} \right] = N_K \left[\frac{\text{Gy}}{\text{C}} \right] \cdot Q(r) [C] \cdot \frac{T[K]}{T_0[K]} \cdot \frac{P_0[hPa]}{P[hPa]} \cdot k_Q \cdot k_{Ka \rightarrow Dw} \cdot 1 \left[\frac{1}{\text{min}} \right] \quad (9)$$

where:

- N_K detector calibration factor (from the calibration certificate),
- Q measured charge Q over one minute,
- T current measured temperature,
- T_0 reference temperature (from the ionization chamber calibration certificate),
- P_0 reference air pressure (from the ionization chamber calibration certificate),
- P current measured air pressure,
- K_Q radiation quality correction factor (from the calibration certificate). The XRS generator quality is approximately equivalent to TW30,
- $k_{Ka \rightarrow Dw}$ correction factor for the PTW type 34013 ionization chamber, used for converting Air Kerma values to absorbed dose in water.

Table 5 presents the mean values and standard deviations of the calculated percentage differences between the XRS generator dose rate from the calibration certificate and the dose rate obtained from the measurements. A Wilcoxon test was conducted for the calculated differences. The significance level (α) was set at 0.05 for rejecting the null hypothesis. The statistical parameters of the measurements presented in this study were calculated using the following formulas:

- mean value:

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i \quad (10)$$

- standard deviation:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \quad (11)$$

where x_i is the value of the measurement and N is a total number of measurements^{14,15}.

Table 5. Mean and standard deviation of the calculated percentage differences between the certificate data and the performed measurements for distances in the range of 3 mm < z < 45 mm.

	Mean [%]	Standard deviation [%]	p value*
Measurement data	-1.3	1.0	0.0003**

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

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

The mean value of the percentage differences is -1.3%, with a standard deviation of 1.0%. These relatively small values of the mean and standard deviation indicate a high agreement between the conducted measurements and the certification data for the XRS generator.

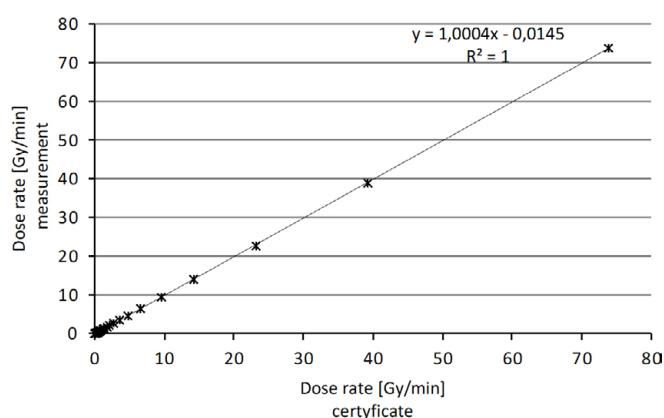


Figure 4. Dose rate values from the certificate and measurements.

The comparison of these results is presented in a plot (Figure 4), where one axis represents the Dose Rate values from the certification, while the other corresponds to the Dose Rate values obtained from measurements of the XRS generator. Full agreement is achieved when the data points align along the $y = x$ line. Analysis of Figure 4, 5 and Table 5 indicates a high level

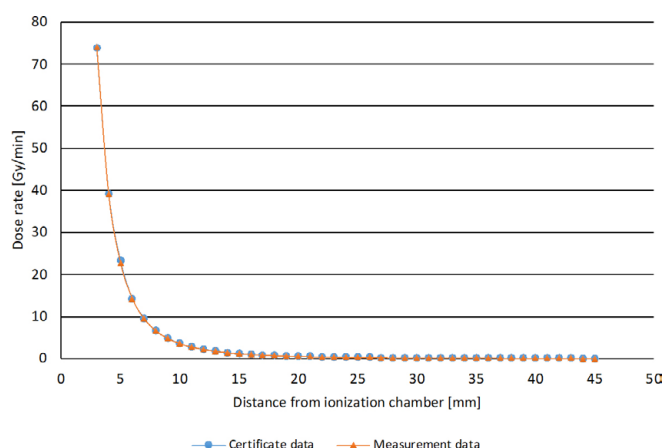


Figure 5. Comparison of the calibrated depth dose rate curve using measured values.

of agreement between the certification data and the measured results, with most values falling within the 5% compliance range.

Reproducibility of XRS output

To assess the reproducibility of the XRS output performance, a TN34013 ionization chamber was employed, and all measurements were conducted in a dedicated water phantom to ensure consistent experimental conditions. Reproducibility was evaluated by performing five consecutive measurements under fixed beam parameters of 50 kV and 40 μ A, with an exposure time of 1 minute for each measurement. The standard deviation across these measurements was 0.055%, indicating excellent consistency and confirming the high stability and reliability of the INTRABEAM 600 system under the specified conditions.

Independent Calculation of Treatment time with a Spherical Applicator

To assess the impact on the X-ray beam and dose distribution when a spherical applicator is attached to the X-ray probe, the output of the source is adjusted by the applicator transfer function $ATF(z)$. For depths where $z \geq$ the radius of the spherical applicator, the $ATF(z)$ is defined as the ratio of the dose rate to water with the spherical applicator $\dot{D}_{wA}(z)$ to the dose rate to water without the applicator $\dot{D}_w(z)$, as expressed in Equation 9. The manufacturer provides a set of ATF tables for each spherical applicator.

$$ATF(z) = \frac{\dot{D}_{wA}(z)}{\dot{D}_w(z)} \quad (12)$$

The treatment time in minutes is calculated as shown in Equation 13:

$$Treatment\ time = \frac{Dose}{\dot{D}_w(z) \cdot ATF(z)} \quad (13)$$

In this study, the treatment time for each spherical applicator was calculated from its surface to a depth of 45 mm to deliver a dose of 20 Gy. The calculations were performed using the Calibration v4.0 method and the TARGIT approach. Tables 6 and 7 present the percentage differences between the treatment times calculated by INTRABEAM 600 and radiance, as well as the percentage differences between the treatment times calculated by INTRABEAM 600 and our own calculations for each spherical applicator, corresponding to the Calibration v4.0 and TARGIT methods, respectively.

For the Calibration V4.0 method, the largest percentage difference in treatment time between INTRABEAM and radiance was observed for the 20 mm diameter applicator $-1.9 \pm 1.1\%$. The difference between INTRABEAM and our own calculations was $-1.9 \pm 1.2\%$.

Conversely, the smallest percentage difference in treatment time between INTRABEAM and radiance was obtained for the 50 mm applicator, measured at $-1.4 \pm 0.2\%$. Regarding the differences between INTRABEAM and our own calculations, the

Table 6. Percentage Differences in Treatment Time for the Calibration V4.0 method.

Calibration V4.0						
Spherical applicator [mm]	Difference Treatment Time INTRABEAM - RADIANCE [%]			Difference Treatment Time INTRABEAM - CALCULATIONS [%]		
	Mean [%]	Standard deviation [%]	p value [*]	Mean [%]	Standard deviation [%]	p value [*]
15	-1.8	0.7	<0.001	-1.7	1	<0.001
20	-1.9	1.1	<0.001	-1.9	1.2	<0.001
25	-1.7	0.6	<0.001	-1.6	0.7	<0.001
30	-1.7	0.4	<0.001	-1.5	0.6	<0.001
35	-1.7	0.5	0.0003	-1.7	0.8	0.0003
40	-1.5	0.3	0.0004	-1.2	0.5	0.0004
45	-1.5	0.3	0.0015	-1.5	0.5	0.0015
50	-1.4	0.2	0.0033	-1.2	0.4	0.0033

* The p-value was calculated using the Wilcoxon signed-rank test. The p-value has a statistical significance of difference ($p < 0.05$)

Table 7. Percentage Differences in Treatment Time for the TARGIT method.

TARGIT						
Spherical applicator [mm]	Difference Treatment Time INTRABEAM - RADIANCE [%]			Difference Treatment Time INTRABEAM - CALCULATIONS [%]		
	Mean [%]	Standard deviation [%]	p value [*]	Mean [%]	Standard deviation [%]	p value [*]
15	-1.8	0.6	<0.001	-1.7	0.9	<0.001
20	-1.8	0.6	<0.001	-1.8	0.9	<0.001
25	-1.7	0.5	<0.001	-1.6	0.7	<0.001
30	-1.6	0.3	<0.001	-1.4	0.6	<0.001
35	-1.6	0.4	0.0003	-1.5	0.8	0.0003
40	-1.6	0.4	0.0004	-1.3	0.5	0.0004
45	-1.5	0.3	0.0015	-1.2	0.6	0.0015
50	-1.3	0.2	0.0033	-1.3	0.4	0.0033

* The p-value was calculated using the Wilcoxon signed-rank test. The p-value has a statistical significance of difference ($p < 0.05$)

smallest differences were observed for the 50 mm and 40 mm applicators, amounting to $-1.2 \pm 0.4\%$ and $-1.2 \pm 0.5\%$, respectively.

Analyzing the TARGIT method (Table 7), the largest percentage differences in treatment time between INTRABEAM and radiance were observed for the 15 mm and 20 mm diameter applicators, amounting to $-1.8 \pm 0.6\%$. The smallest difference was found for the 50 mm applicator $-1.3 \pm 0.2\%$.

Regarding the percentage differences in treatment time between INTRABEAM and our own calculations, the largest difference was observed for the 20 mm applicator $-1.8 \pm 0.9\%$, while the smallest difference was found for the 45 mm applicator $-1.2 \pm 0.6\%$.

The analyses indicate that both radiance and our own calculations can be used as independent checks of the treatment time calculated by INTRABEAM before the start of treatment.

Isotropy function of the INTRABEAM 600 XRS

X-ray generator isotropy means that X-ray radiation is emitted uniformly in all directions, implying that its intensity does not depend on the observation angle relative to the source.

Measuring the isotropy of an XRS generator requires a full rotation around its axis while recording the emitted radiation. To ensure precise positioning and repeatability of settings, the water phantom is equipped with a locking mechanism that secures the rotating table in eight positions at 45° intervals. The locking mechanism is implemented using a clamping screw, allowing the rotational feedthrough to be fixed in each of these positions. Measurements were conducted at 45° increments, with an acquisition time of 60 seconds for each position, using an ionization chamber mounted on the side of the water phantom.

Table 8 and Figure 6 present the obtained isotropy measurement values for 8 measurement points. Below are presented the detailed results.

Table 8. The obtained isotropy measurement values.

Mean Charge [pC]	Standard Deviation [pC]	Min Value [pC]	Max Value [pC]
13.08	0.06	13.00	13.17

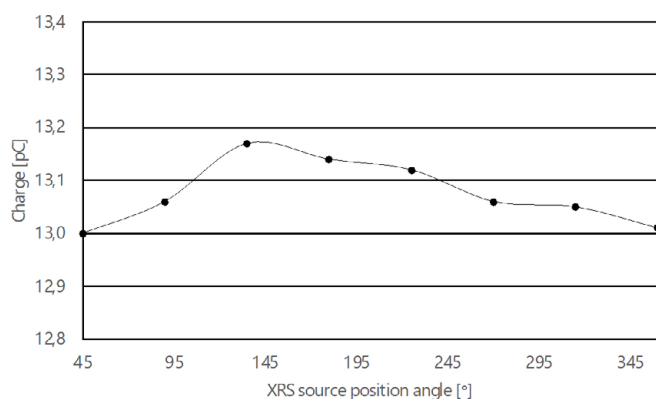


Figure 6. Measurement data from the isotropy test.

The obtained measurement results are as follows: the mean charge is 13.08 pC, with a standard deviation of 0.06 pC. The minimum value recorded is 13.00 pC, and the maximum value is 13.17 pC. Based on the data presented in **Figure 6**, it can be concluded that the isotropy function for the XRS generator is accurate, making it appropriate for clinical applications.

Conclusions

This study confirmed that the INTRABEAM 600 system demonstrates high stability, precision, and clinical reliability when subjected to comprehensive commissioning measurements, rigorous quality assurance procedures, and independent treatment time verification. Dynamic offset analysis revealed minimal deviations from the reference (0,0) point, confirming correct beam bending alignment, while the Output Check test verified the stability of the XRS generator. Depth dose rate curve measurements showed a mean percentage difference of $-1.3 \pm 1.0\%$ from the certification data, indicating strong agreement and compliance with established standards. Several potential sources of uncertainty and limitations were identified during the work. These include the mechanical precision required for probe tip positioning, the influence of en-

vironmental variations on ionization chamber readings, and the inherent measurement uncertainties in low-energy X-ray dosimetry. Although these factors were mitigated through repeated measurements, precise alignment, and environmental corrections, they remain relevant for clinical implementation. These factors may influence the applicability and reproducibility of the results in other clinical environments. Most findings were consistent with expectations based on previous studies on INTRABEAM system commissioning^{2,3}, with deviations generally within the 5% compliance range reported in the literature. The strong correlation between the Calibration v4.0 and TARGIT methods was anticipated, as both have been validated in earlier phantom and clinical research¹². Unexpectedly, the largest treatment time discrepancies between INTRABEAM and independent calculations were observed for smaller applicators (15–20 mm), whereas earlier reports often noted greater differences for larger applicators due to beam attenuation effects². This suggests that, for smaller applicators, subtle geometric or algorithmic factors may have a proportionally greater impact on calculated times. In relation to the literature review, these results reinforce that integrating independent verification procedures such as those based on Calibration v4.0 and TARGIT strengthens the robustness of IORT quality assurance. This aligns with recommended best practices for high-precision IORT delivery^{1,4,5}. Furthermore, the close match between our measurements and radiance software simulations confirms the suitability of radiance as a planning and verification tool, consistent with other studies validating Monte Carlo-based IORT planning systems^{10,11}. In conclusion, this work not only validates the INTRABEAM 600 system for clinical use under our commissioning and QA conditions but also emphasizes the importance of meticulous positioning, environmental corrections, and cross-checking of methods to ensure treatment accuracy. While most findings confirm existing knowledge, the applicator-size-dependent discrepancies observed in this study warrant further multi-center research to refine IORT dosimetry and verification protocols.

References

- Sethi A, Gros S, Brodin P, et al. Intraoperative radiation therapy with 50 kV x-rays: A multi-institutional review. *J Applied Clin Med Phys*. 2024;25(3). doi:10.1002/acm2.14272
- Shaikh MY, Joiner MC, Nalichowski A, Kumaraswamy LK, Burmeister J. Evaluation of the dosimetric impact of manufacturing variations for the INTRABEAM x-ray source. *J Applied Clin Med Phys*. 2020;21(3):20-31. doi:10.1002/acm2.12809
- Muralidhar K, Rout B, Mallikarjuna A, Poornima A, Murthy PN. Commissioning and quality assurances of the Intrabeam Intra-Operative radiotherapy unit. *Int J Cancer Ther Oncol*. 2014;2(4):020415. doi:10.14319/ijcto.0204.15
- Pascual JSG. Treatment Protocols and Outcomes of Intraoperative Radiotherapy for Brain Metastases: A Systematic Review. *EJMO*. Published online 2022. doi:10.14744/ejmo.2021.29249
- Ylanan AMD, Pascual JSG, Cruz-Lim EMD, Ignacio KHD, Cañal JPA, Khu KJO. Intraoperative radiotherapy for glioblastoma: A systematic review of techniques and outcomes. *Journal of Clinical Neuroscience*. 2021;93:36-41. doi:10.1016/j.jocn.2021.08.022
- Giordano FA, Brehmer S, Abo-Madyan Y, et al. INTRAGO: intraoperative radiotherapy in glioblastoma multiforme – A Phase I/II dose escalation study. *BMC Cancer*. 2014;14(1). doi:10.1186/1471-2407-14-992
- “INTRABEAM 600 User Manual,” 2022. Online. Available: www.zeiss.com/med
- “INTRABEAM * Spherical Applicator User Manual,” 2019. Online. Available: www.zeiss.com/med
- “INTRABEAM* Water Phantom,” 2022. Online. Available: www.meditec.zeiss.com
- GMV, “INTRAOPERATIVE RADIOTHERAPY TREATMENT PLANNING SYSTEM.” Online. Available: <https://gmvdrive.gmv.com/index.php/s/JDdA3LOpYmgNgCC>

11. Valdivieso-Casique MF, Rodríguez R, Rodríguez-Bescóset S, et al. RADIANCE-A planning software for intra-operative radiation therapy. *Translational Cancer Research*. 2015;4(2). doi: 10.3978/j.issn.2218-676X.2015.04.05
12. Watson PGF, Popovic M, Seuntjens J. Determination of absorbed dose to water from a miniature kilovoltage x-ray source using a parallel-plate ionization chamber. *Phys Med Biol*. 2017;63(1):015016. doi:10.1088/1361-6560/aa9560
13. Shaikh MY, Joiner MC, Nalichowski A, Kumaraswamy LK, Burmeister J. Evaluation of the dosimetric impact of manufacturing variations for the INTRABEAM x-ray source. *J Applied Clin Med Phys*. 2020;21(3):20-31. doi:10.1002/acm2.12809
14. Bhalerao S, Parab S. Choosing statistical test. *Int J Ayurveda Res*. 2010;1(3):187. doi:10.4103/0974-7788.72494
15. Bellolio MF, Serrano LA, Stead LG. Understanding statistical tests in the medical literature: which test should I use? *Int J Emerg Med*. 2008;1(3):197-199. doi:10.1007/s12245-008-0061-z