

Enabling Rotational Management for Intracranial Stereotactic Treatments on Halcyon Using SGRT and the TruPose™ Head Adjuster

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Product **Standard Imaging TruPose™ Head Adjuster**



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1 Abstract

The Halcyon™ linear accelerator offers compelling clinical advantages for radiotherapy including a wide field size (28 cm), rapid CBCT acquisition (~17 seconds), and high nominal dose rate (800 MU/min). However, its bore geometry architecture imposes a critical constraint for intracranial stereotactic radiosurgery (SRS): the treatment couch provides only three degrees of freedom (3-DOF), with no native capacity for rotational correction.

Until recently, rotational setup corrections on Halcyon were therefore limited by the absence of a 6-DOF couch, motivating the clinical evaluation of manual SGRT-guided solutions such as the TruPose™ Head Adjuster. Although a 6-DOF couch option has recently become available for Halcyon, implementation requires a major system upgrade and significant capital investment, which may limit adoption among centers already equipped with earlier systems. Furthermore, SGRT-guided rotational correction remains clinically relevant as a complementary strategy, enabling rapid pre-imaging rotational adjustments and facilitating fine corrections after patient motion without the need for additional CBCT acquisitions.

This paper presents a validated clinical workflow developed at the ORLAM Group (Villeurbanne, France) that addresses this limitation through the combined use of AlignRT® surface guided radiation therapy (SGRT) and the Standard Imaging TruPose™ Head Adjuster. The workflow was preceded by phantom end-

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to-end testing establishing SGRT–CBCT rotational correlation (Yaw: $0.1^\circ \pm 0.1$; Roll: $0.1^\circ \pm 0.1$; Pitch: $0.3^\circ \pm 0.2$), and subsequently deployed clinically in 24 intracranial SRS patients. Residual rotational errors were compared against a reference cohort of 24 patients treated on the TrueBeam® Edge with its native 6-DOF couch and a cohort of 24 patients treated on the Halcyon™ before implementation of the TruPose™ using only a SGRT-guided workflow.

Results demonstrate that the SGRT–TruPose combination constitutes a viable, safe, and reproducible method for delivering 6-DOF intracranial SRS on a 3-DOF platform, with ongoing optimization of mask fabrication and region-of-interest (ROI) configuration to further reduce pitch errors.

2 Introduction & Background

2.1 The Halcyon Platform: Benefits and Operational Context

The Halcyon™ system (Varian Medical Systems) represents a class of ring-gantry linear accelerators designed to streamline radiotherapy delivery. The ORLAM Group initiated treatments on the Halcyon platform on February 15, 2018, and has treated over 30,000 patients to date, including both standard and stereotactic indications.

Key clinical advantages of the platform include:

- **Wide radiation field size:** 28 cm, compared to 22 cm on the TrueBeam Edge, supporting a broader range of treatment configurations.
- **Rapid image guidance:** CBCT acquisition in approximately 17 seconds, enabling high-frequency imaging without substantially extending treatment sessions.
- **High nominal dose rate:** 800 MU/min, facilitating delivery of high-dose stereotactic fractions in clinically acceptable timeframes.
- **Advanced MLC technology:** A dual-layer multi-leaf collimator supporting IMRT, VMAT, and SRS delivery.

These characteristics make the platform well-suited for high-precision stereotactic treatments from a dose delivery perspective (Li et al, 2019; Palaysi et al, 2026). However, implementation of intracranial SRS on the Halcyon requires specific workflow accommodations not needed on conventional gantry systems.

2.2 The Operational Challenge: Rotational Management on the Halcyon Platform

The Halcyon bore architecture introduces several practical challenges for intracranial stereotactic radiosurgery (SRS). Unlike conventional C-arm linear accelerators, the system operates within a closed bore environment, eliminating the use of a light field for setup verification and limiting the utility of conventional room laser alignment at treatment isocenter.

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Historically, the most significant limitation for intracranial SRS was the absence of rotational correction capability. The original Halcyon treatment couch provided translational corrections only (lateral, longitudinal, and vertical), without native pitch, roll, or yaw adjustment. This limitation is particularly relevant in intracranial SRS, where small rotational errors may result in clinically meaningful target displacement, especially for lesions located away from isocenter.

Although a 6-DOF couch option has recently become available for Halcyon, many systems currently in clinical operation remain equipped with the original 3-DOF configuration. Furthermore, SGRT-guided rotational management may offer workflow advantages beyond couch-based correction alone, including rapid pre-imaging corrections and the potential for fine adjustments following patient motion without requiring additional imaging.

These considerations motivated the development of a practical SGRT-guided rotational correction workflow adapted to the Halcyon treatment environment.

2.3 Prior Work and Study Objective

The ORLAM Group's experience with SGRT on the Halcyon platform was previously reported by Nguyen et al. [1], establishing the feasibility of surface-guided patient positioning within the Halcyon bore environment. Building upon this experience, the present work focuses specifically on intracranial SRS, where rotational accuracy requirements are substantially more stringent.

The objective of this study was to develop, validate, and clinically implement a workflow combining AlignRT® surface-guided radiation therapy (SGRT) and the TruPose™ Head Adjuster to provide comprehensive rotational management on the Halcyon platform. The study was designed to address two key questions: first, whether SGRT-derived rotational measurements accurately correlate with CBCT-based registrations; and second, whether this workflow can achieve rotational positioning performance comparable to a native 6-DOF treatment platform in clinical practice.

2.4 Study Rationale

Although a 6-DOF couch option has recently become available for the Halcyon platform, its implementation requires a major hardware upgrade and substantial capital investment. Furthermore, there remains limited published evidence regarding SGRT-guided rotational management strategies for intracranial SRS on Halcyon.

The objective of this study was to determine whether a workflow combining AlignRT® SGRT and the TruPose™ Head Adjuster could provide clinically acceptable rotational management for intracranial SRS on the Halcyon platform. Specifically, the study sought to (1) validate the agreement between SGRT-detected and CBCT-measured rotational offsets, and (2) evaluate the clinical performance of the workflow relative to a reference cohort treated on a native 6-DOF platform.

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3 Phantom Validation & End-to-End Testing

3.1 Study Design

Prior to clinical implementation, a dedicated phantom end-to-end study was conducted to characterize the SGRT–CBCT correlation in the Halcyon environment. The study utilized a STEEV™ anthropomorphic skull phantom (Sun Nuclear) fitted with an open 5-point thermoplastic mask (Macromedics), replicating the clinical immobilization configuration intended for patient treatments.

The study was designed to evaluate two specific questions: (1) the accuracy with which AlignRT® detects intentional rotational offsets applied to the phantom; and (2) whether those offsets, once detected, are confirmed by independent CBCT acquisition and offline realignment. This two-modality correlation approach is critical on the Halcyon, where no light field or internal laser reference is available to verify the pre-CBCT setup state.

3.2 Methodology

Intentional angular offsets were applied to the phantom across three rotational axes (yaw, roll, and pitch) in increments spanning 0° to 2°. For each offset configuration:

1. The AlignRT® system detected and recorded the applied offset relative to the reference surface.
2. A CBCT was acquired and the resultant image was registered offline against the planning CT using 6-DOF registration in the treatment planning system.
3. The rotational components of the CBCT-derived registration were compared against the corresponding AlignRT® measurements to assess inter-modality agreement.

This process produced a correlation dataset across the full clinical range of expected patient positioning errors.

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3.3 Baseline SGRT–CBCT Correlation Results

The end-to-end testing demonstrated strong agreement between AlignRT® surface detection and CBCT-derived rotational registration across all three axes. Baseline correlation results were as follows:

Axis	SGRT–CBCT Correlation (Mean ± SD)
Yaw	0.1° ± 0.1°
Roll	0.1° ± 0.1°
Pitch	0.3° ± 0.2°

Table 1. Phantom test results showing rotational offsets relative to the SGRT reference after correction using the TruPose Head Adjuster.

Pitch exhibited the largest mean deviation ($0.3^\circ \pm 0.2^\circ$), which is consistent with the expected susceptibility of pitch measurement to subtle chin flexion or extension in the mask. These results confirm that AlignRT® provides clinically reliable rotational offset detection on the Halcyon platform.

The phantom validation data demonstrate that AlignRT® can reliably detect rotational setup errors within the Halcyon environment. However, accurate detection alone does not ensure clinical correction. On the original Halcyon platform, rotational offsets identified by SGRT cannot be compensated through couch motion and therefore require an alternative correction strategy.

Within the proposed workflow, the TruPose™ Head Adjuster provides a practical means of translating SGRT-detected rotational offsets into clinically actionable corrections. The phantom study therefore established the technical foundation necessary for subsequent clinical implementation and evaluation of the complete SGRT–TruPose rotational management workflow.

4 The TruPose Head Adjuster: Hardware Solution

4.1 System Overview and Rationale

The Standard Imaging TruPose™ Head Adjuster was selected as a practical mechanical solution to address the rotational correction limitations associated with the Halcyon 3-DOF treatment couch. Discussions between the ORLAM Group and Standard Imaging regarding the development of a Halcyon-compatible rotational adjustment device began in 2022. Following iterative design modifications to accommodate the

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Halcyon bore geometry, the current TruPose configuration was introduced into clinical use at the ORLAM Group on October 17, 2024.

The TruPose system provides manual rotational adjustment capability through precision control knobs, enabling therapists to compensate for residual pitch, roll, and yaw deviations identified by AlignRT® without requiring couch rotation. Weighing approximately 4 kg, the device is sufficiently lightweight to be installed and removed from the Halcyon treatment couch without significantly impacting the clinical workflow.

When combined with SGRT, the TruPose workflow effectively extends the rotational management capabilities of a 3-DOF Halcyon platform by allowing therapists to identify and manually compensate for rotational setup deviations prior to image-guided verification. Although it is not intended to replace a robotic 6-DOF treatment couch, this approach may provide a practical “6DoF-like” positioning workflow for institutions lacking native rotational correction capabilities.

The recent availability of a dedicated 6-DOF couch for Halcyon systems represents an important technological advancement. However, implementation requires migration to Halcyon v5 and acquisition of additional hardware, which may limit adoption among centers operating earlier Halcyon installations. In this context, the TruPose Head Adjuster remains a cost-effective and immediately deployable option for rotational management.

Furthermore, even in centers equipped with a native 6-DOF couch, the TruPose system may retain clinical utility as a pre-positioning aid. SGRT-guided manual rotational adjustments performed prior to CBCT acquisition could potentially reduce the magnitude of subsequent couch corrections, streamline patient setup, and improve workflow efficiency. These potential applications warrant further investigation.

An important hardware compatibility consideration is that the Vision RT Head Adjuster model designed for conventional C-arm linear accelerators is not compatible with the Halcyon bore dimensions. A dedicated Halcyon-specific configuration was therefore developed and clinically evaluated in collaboration with Standard Imaging.

4.2 Mask System Compatibility

At the ORLAM Group, the TruPose system has been successfully evaluated with multiple immobilization solutions, including:

- Macromedics DSPS (Dynamic Stereotactic Positioning System) for intracranial SRS/SRT treatments.
- 5-pin S-type mask frames for conventional (non-stereotactic) cranial treatments.

In addition, the TruPose system is designed to be compatible with open 3-point thermoplastic mask systems, such as the Orfit Open 3-Point configuration, although this specific configuration has not yet been evaluated within the ORLAM Group.

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This flexibility enables integration of the TruPose workflow into existing institutional immobilization practices without requiring migration to a single proprietary mask platform.

4.3 Initial Tests on Volunteers

Prior to clinical implementation, the TruPose Head Adjuster underwent a series of evaluations on healthy volunteers. These tests were designed to assess mechanical performance within the Halcyon bore, evaluate accessibility of the adjustment knobs under simulated treatment conditions, and identify potential ergonomic or workflow constraints before first patient use.

Volunteer testing confirmed that rotational adjustments could be performed safely and reproducibly within the confined Halcyon bore environment. Treatment staff reported adequate accessibility to the adjustment controls, and the overall correction procedure was completed within a clinically acceptable timeframe, supporting subsequent clinical deployment.

5 Immobilization Strategy

5.1 Mask Selection

Open thermoplastic masks specifically designed for stereotactic treatments are utilized for all intracranial SRS procedures performed on the Halcyon platform at the ORLAM Group. Within the TruPose workflow, the Macromedics DSPS (Dynamic Stereotactic Positioning System) has been clinically validated for intracranial SRS/SRT treatments. In addition, the TruPose workflow has been evaluated with 5-pin S-type mask frames for conventional (non-stereotactic) cranial treatments. The system is also compatible with open 3-point thermoplastic mask configurations, such as the Orfit Open 3-Point system, although this specific configuration has not yet been clinically evaluated within the ORLAM Group.

Open-mask configurations were selected at our institution because they maximize the amount of exposed facial anatomy available for SGRT tracking while preserving direct visual assessment of patient posture and alignment prior to final mask fixation. These characteristics were considered advantageous for the SGRT-guided rotational correction workflow implemented on the Halcyon platform.

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5.2 Mask Fabrication Technique

Careful fabrication of the open-face thermoplastic mask is an essential step for achieving reproducible patient immobilization and optimal SGRT performance. For intracranial SRS/SRT treatments, particular attention should be paid to patient head positioning during mask molding. The chin should be maintained in a slightly flexed (neutral) position to maximize facial surface visibility for SGRT tracking. In contrast, an elevated chin position, commonly used for head-and-neck treatments, should be avoided for intracranial applications.

The ring-gantry architecture of the Halcyon™ provides the AlignRT® camera pods with an unobstructed view of the patient's facial surface throughout patient setup, unlike conventional C-arm linacs where the gantry or onboard imaging components may partially obstruct the camera field of view. Taking advantage of this geometry, different facial regions of interest (ROIs) were evaluated during commissioning. No camera occlusion was observed, even when using relatively small ROIs (Figure 4). Consequently, whenever possible, the mask opening should be restricted to the minimum facial area required for reliable SGRT tracking, avoiding unnecessary exposure of deformable soft-tissue regions such as the cheeks. Preserving mask coverage over these areas improves immobilization while maintaining adequate facial surface visibility for accurate SGRT guidance.

To improve the reproducibility of mask fabrication, a hair dryer operated in cool-air mode is used during the cooling phase of the thermoplastic material. Accelerated cooling promotes rapid hardening while allowing precise molding of key anatomical regions, particularly the forehead, chin, occiput, and nape of the neck (Figure 1). The thermoplastic mask should be allowed to fully cool and harden before CT simulation to minimize post-fabrication deformation and ensure stable immobilization throughout treatment.

Based on our institutional experience, this standardized fabrication technique appears to improve mask conformity and reduce operator-dependent variability. Although these observations have not yet been formally quantified, mask fabrication consistency appears to be an important contributor to residual setup uncertainty, particularly for pitch rotations. Further investigations are ongoing to determine whether additional standardization of the fabrication process can further reduce rotational setup variability during routine clinical implementation.

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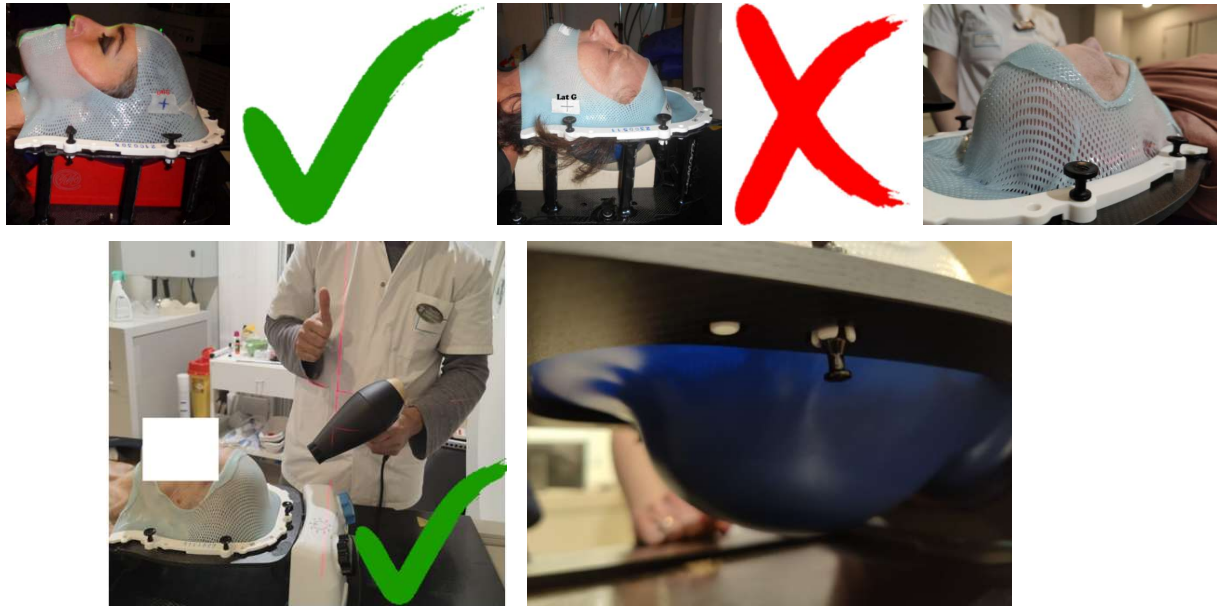


Figure 1 - Standardized fabrication of the open-face thermoplastic mask. (A) Patient positioning with the chin in slight flexion to optimize facial surface visibility for SGRT. (B) Careful molding of the forehead, chin, occiput, and nape of the neck. (C) Application of cool air using a hair dryer to accelerate cooling and hardening of the thermoplastic mask in key immobilization regions prior to CT simulation.

6 Clinical Workflow for Halcyon SRS/SRT with TruPose

The intracranial SRS workflow developed at our institution combines SGRT-guided patient positioning [5], manual rotational adjustment using the TruPose Head Adjuster, conventional translational couch shifts, and CBCT verification to achieve a high level of positional confidence prior to treatment delivery.

6.1 Step 1 – Initial Patient Positioning

The patient is initially positioned using the AlignRT® Postural Video and Deformation Module with the thermoplastic mask placed on the patient but not yet secured. Real-time surface guidance is used to align the patient with the reference surface acquired during CT simulation by manually correcting gross positional and rotational discrepancies.

Once the residual rotational errors are reduced to within approximately 3° , the treatment couch is translated to correct the remaining translational offsets while the mask remains unsecured. Performing this initial positioning step before final mask fixation enables correction of large rotational deviations through patient repositioning rather than mechanical intervention. As a result, the magnitude of subsequent

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TruPose rotational adjustments is minimized, reducing both workflow complexity and the time the patient spends under full immobilization.

6.2 Step 2 – Mask Securing and SGRT-Guided Rotational Correction

Following satisfactory postural alignment, the thermoplastic mask is secured to the immobilization frame. Residual rotational errors are then continuously monitored using AlignRT®.

The RTD (Real-Time Deltas) displayed by AlignRT® provide immediate visual feedback during the correction process. Using the TruPose adjustment knobs, the treating team performs real-time pitch, roll, and yaw corrections while observing the corresponding rotational errors update continuously on the SGRT display. This closed-loop feedback enables rapid and intuitive optimization of patient rotational alignment without repeated imaging.

Based on institutional experience, the following action levels were established:

- Yaw: $\leq 0.5^\circ$
- Roll: $\leq 0.5^\circ$
- Pitch: $\leq 1.0^\circ$

The slightly larger tolerance adopted for pitch reflects its increased sensitivity to mask fabrication variability and patient-specific anatomical factors observed during clinical implementation.

Rotational adjustments are continued under continuous SGRT monitoring until all rotational offsets are within the institutional tolerances prior to CBCT acquisition.

6.3 Step 3 – Translational Correction and Transfer to the Treatment Isocenter

After rotational optimization, two workflow options may be used depending on the clinical situation.

Option 1 – Translational correction at the Halcyon virtual isocenter

When positioning is performed at the Halcyon virtual isocenter, residual translational offsets are corrected using standard couch translations while rotational alignment is maintained with TruPose. This approach allows both rotational and translational errors to be minimized before the patient is translated to the treatment isocenter.

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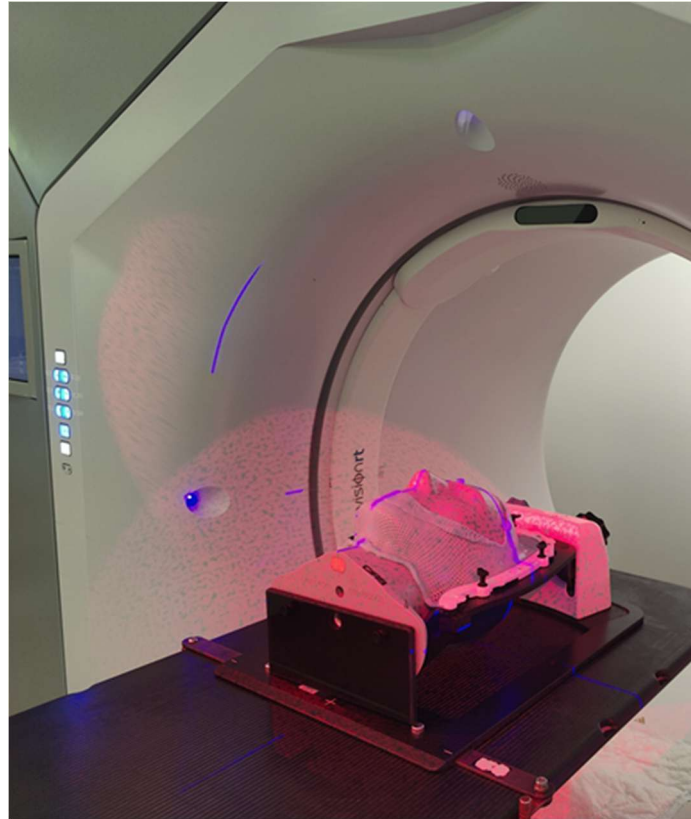


Figure 2 - Setup for Option 1 workflow on the Halcyon platform showing DPS thermoplastic mask immobilization with TruPose system used for SGRT-guided rotational alignment at the virtual isocenter.

Option 2 – Rotational correction at the treatment isocenter

Alternatively, the patient may be transferred directly to the treatment isocenter with small residual rotational errors remaining. The radiation therapists then move to the rear of the Halcyon bore (Figure 3) and perform the final TruPose pitch, roll, and yaw adjustments while monitoring the in-bore AlignRT® (Figure 4) Real-Time Delta (RTD) values. Because couch translations are not available during this stage, only rotational corrections are performed.

Since CBCT-based image guidance is mandatory on the Halcyon platform, any remaining translational offsets are subsequently corrected using the image-guided couch shifts before treatment delivery.

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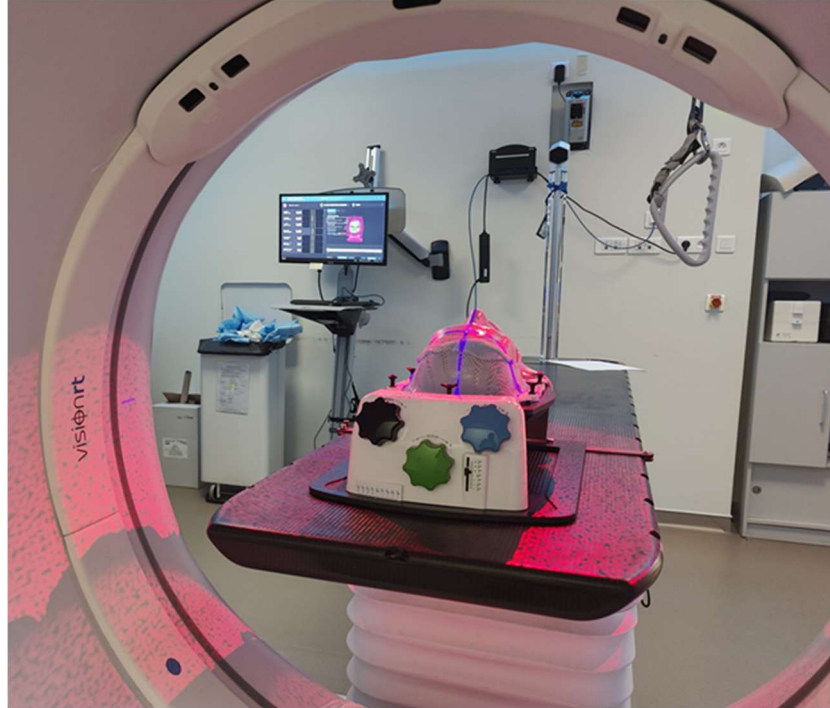


Figure 3 - In-bore Halcyon setup for Option 2 workflow illustrating patient immobilization with a Macromedics DSPS mask, TruPose rotational adjustment system accessible at the rear of the bore, and real-time AlignRT® SGRT display used for intrafraction rotational monitoring.

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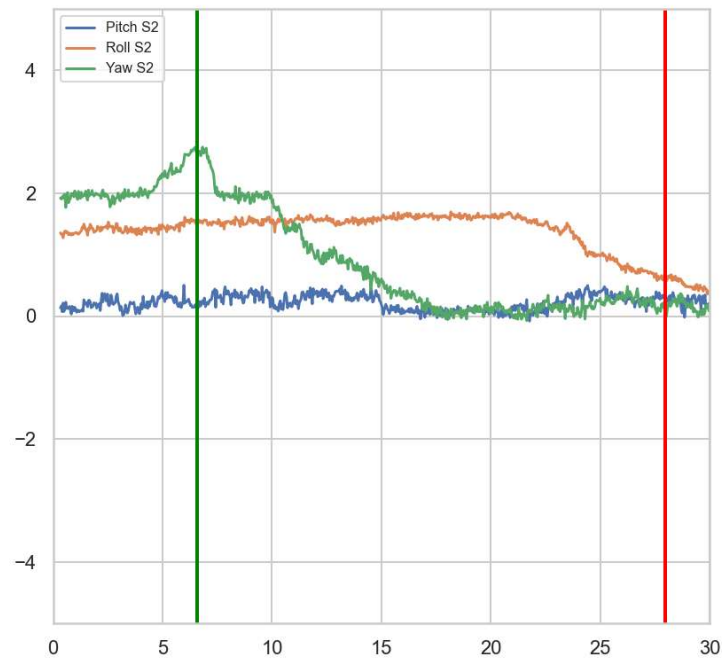


Figure 4 - Example of AlignRT rotation values with pitch, roll, and yaw correction.

6.4 Step 4 – CBCT Acquisition and Verification

A CBCT acquisition is subsequently performed and registered to the planning CT using the Halcyon online 3-DOF registration tools. This mandatory image-guidance step provides final anatomical verification of patient positioning before treatment delivery and identifies any residual translational discrepancies, which are corrected using couch shifts.

If the CBCT reveals clinically significant anatomical misalignment suggestive of residual rotational error (e.g., due to patient motion or suboptimal SGRT surface monitoring), the patient may be repositioned using the TruPose system under AlignRT® guidance, followed by repeat CBCT acquisition to confirm the corrected treatment position. This verification process is routinely applied for intracranial stereotactic treatments to ensure the required positioning accuracy before irradiation.

The CBCT-confirmed position is considered the final treatment position prior to beam delivery.

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6.5 Step 5 – Post-CBCT Verification and SGRT Reference Reset

Following CBCT-guided translational corrections and any necessary rotational refinements using the TruPose system, a final in-bore AlignRT® surface assessment is performed to verify that the patient remains within the institutional rotational tolerances prior to beam delivery. Real-time delta (RTD) values are reviewed to confirm stable pitch, roll, and yaw alignment.

If required, minor residual rotational adjustments can still be performed using the TruPose system under continuous SGRT guidance within the Halcyon bore. In cases where clinically significant misalignment is detected after CBCT, a repeat CBCT may be acquired following repositioning to ensure accurate verification prior to irradiation.

Once the final treatment position is confirmed, an AlignRT® in-bore reference capture is acquired to redefine the SGRT baseline at the CBCT-verified position. This step resets all RTD values to zero and establishes the reference surface for intra-fraction monitoring during beam delivery.

This combined CBCT–SGRT workflow provides a multi-layer verification strategy, ensuring both anatomical and surface-based confirmation of patient positioning immediately prior to treatment delivery.

7 Region of Interest (ROI) Configuration and Impact

7.1 Clinical Significance of ROI Selection

Region of interest (ROI) definition is a fundamental component of SGRT-based intracranial SRS, as it determines the surface area used for real-time motion tracking and rotational alignment.

In the TruPose workflow implemented on the Halcyon platform, SGRT monitoring is performed under conditions of unobstructed camera geometry, without gantry or imaging system occlusions. In this configuration, rotational tracking is primarily driven by the quality and stability of the acquired surface rather than by ROI selection itself.

Within this context, ROI selection does not appear to significantly influence SGRT-derived rotational measurements. This is in contrast to C-arm linac systems, where gantry-induced occlusions and limited camera angles can increase the sensitivity of tracking performance to ROI definition.

Therefore, on the Halcyon platform, ROI selection is considered a non-critical parameter for rotational accuracy, provided that a sufficiently stable and well-exposed facial surface is available.

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7.2 Comparative ROI Analysis

Three ROI configurations were evaluated to assess their impact on SGRT-derived rotational values during TruPose-guided adjustments (Figure 5).

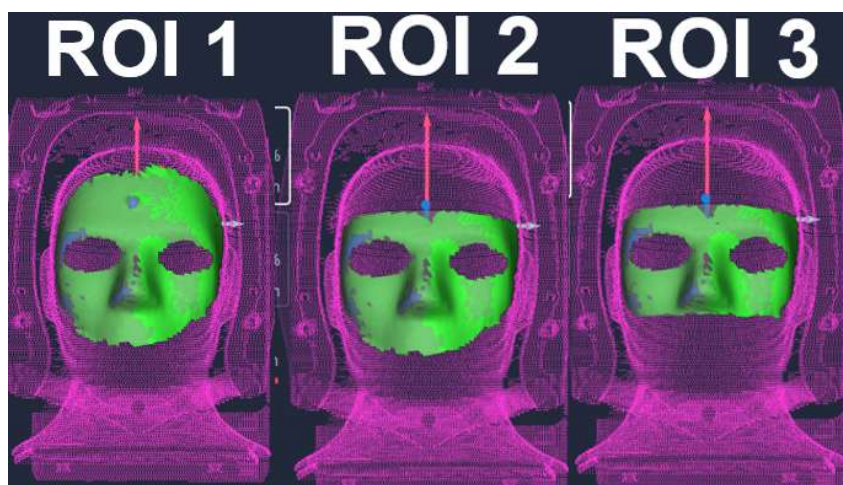


Figure 5 - Across all evaluated configurations, SGRT-derived pitch, roll, and yaw values remained consistent during dynamic adjustments, with no clinically relevant differences observed between ROI setups.

These results indicate that ROI selection does not significantly affect rotational stability in the Halcyon in-bore SGRT configuration. This behavior is likely explained by the absence of gantry-related occlusions and the favorable camera geometry of the bore-mounted SGRT system, which allows robust surface reconstruction across different facial ROI definitions.

These findings differ from C-arm linac environments, where ROI selection can play a more pronounced role in tracking stability due to limited camera perspectives and partial surface visibility.

8 Clinical Results

8.1 Patient Cohort and Study Design

Clinical data were retrospectively collected from three consecutive cohorts of patients undergoing intracranial SRS at the ORLAM Group.

- Halcyon™ V3 without TruPose cohort: twenty-four patients treated from March 2023 to October 2024 using SGRT-only workflow.
- Halcyon™ V3 + TruPose cohort: twenty-four patients treated from October 2024 onward using the SGRT-guided TruPose workflow described in this manuscript.

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- TrueBeam® Edge cohort: twenty-four patients immobilized using the Qfix Encompass™ system and SGRT-guided workflow, treated from June 2024 using the native 6-DOF couch capabilities.

This design allowed for a systematic comparison between positioning accuracy with Halcyon™ SGRT only vs. SGRT TruPose workflows, and Halcyon™ with SGRT TruPose workflow (6DoF-like) vs. TrueBeam™ (6DoF couch) platforms. The inclusion of the TrueBeam™ cohort served as a reference standard due to its full 6DoF correction capabilities.

8.2 Methodology

For all patients and treatment fractions, post-treatment six-degree-of-freedom registrations were reviewed within Eclipse™ to quantify residual rotational errors relative to the planning reference position.

Residual yaw, pitch, and roll deviations were analyzed across the different treatment workflows, with particular emphasis on the Halcyon™ SGRT TruPose workflow. Its rotational positioning performance was benchmarked against the TrueBeam® Edge cohort (6DoF couch). The objective was to investigate whether combining SGRT, TruPose, and an open-face mask could deliver rotational positioning accuracy approaching that of a dedicated 6DoF correction workflow.

The analysis was conducted on a per-patient basis to account for the non-independence of repeated measurements within the same patient, with rotational deviations expressed as absolute values to prevent positive and negative offsets from canceling each other out and to better characterize the magnitude of residual rotational errors.

In addition to rotational accuracy, we evaluated the effects of SGRT on imaging frequency to assess the potential for dose reduction.

Pairwise comparisons were conducted using both the Student's t-test and the non-parametric Mann-Whitney U test. While the Student's t-test was used to compare group means, the Mann-Whitney U test was included to account for the non-normal distribution and skewness that may be observed in absolute rotational error measurements. Statistical significance was defined as a two-sided p-value < 0.05.

8.3 Residual Rotational Error Analysis

Compared with the Halcyon™ SGRT-only cohort, integration of the TruPose significantly reduced residual pitch, roll, and yaw errors (Mann-Whitney U test, $p = 0.047$, $p = 0.001$, and $p = 0.022$, respectively; Table 3). Summary statistics for the residual rotational errors are presented in Table 2.

Compared with the TrueBeam® Edge cohort equipped with a 6DoF couch, residual pitch and roll errors remained significantly higher in the Halcyon™ TruPose group (Mann-Whitney U test: $p < 0.001$ for both axes; Table 3). In contrast, residual yaw errors were comparable between the TrueBeam® Edge and Halcyon™ TruPose groups, with identical mean values (0.53° vs. 0.53° ; Student's t-test, $p = 0.975$; Table 2 and Table 3). However, the distribution of residual yaw errors differed slightly between the two groups, as

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reflected by the Mann-Whitney U test ($p = 0.047$), with median values of 0.30° and 0.46° for the TrueBeam® Edge and Halcyon™ TruPose groups, respectively (Table 2).

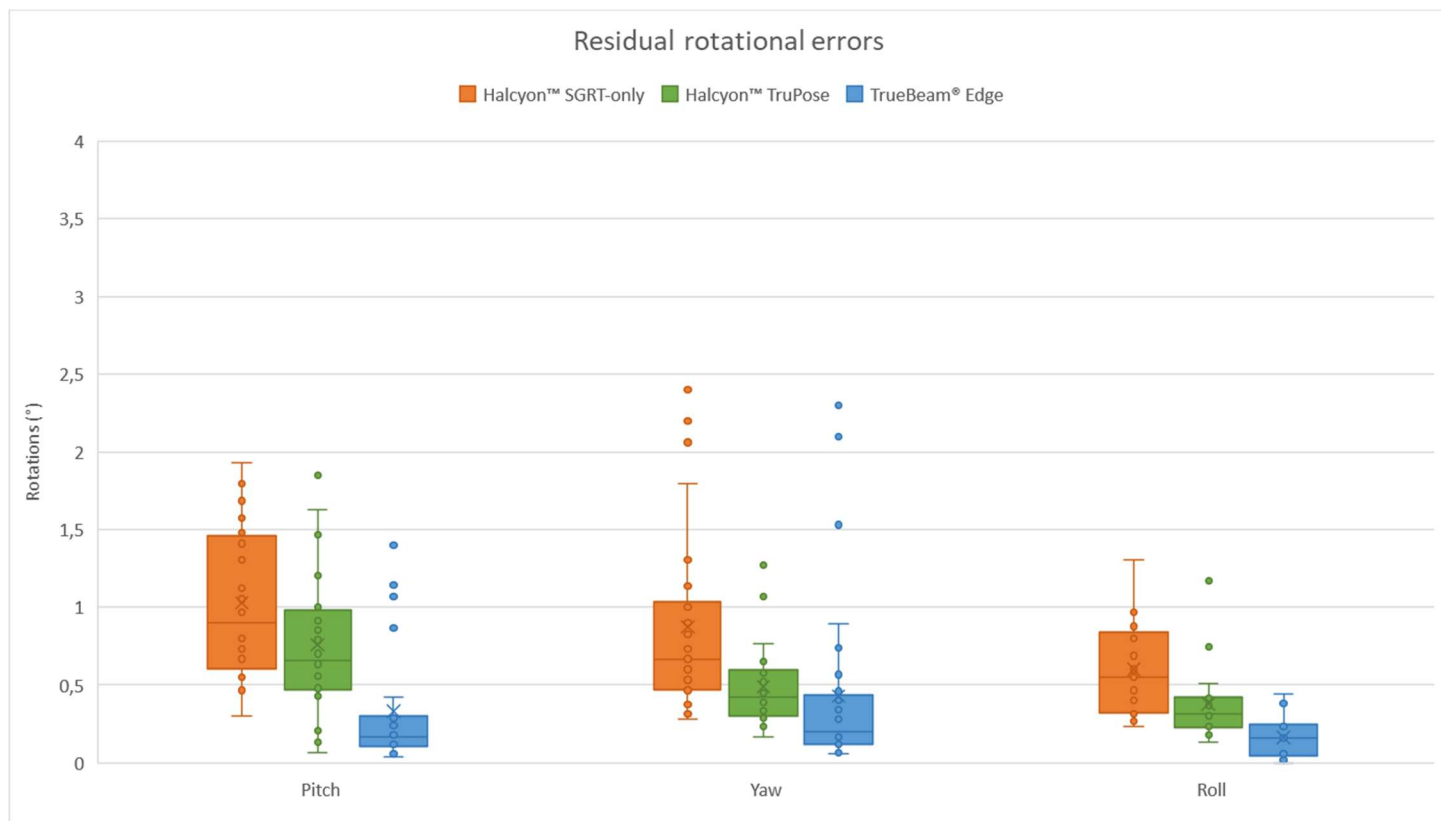


Figure 6 - Boxplots of residual rotational setup errors in pitch, yaw, and roll for Halcyon™ SGRT-only, Halcyon™ TruPose and TrueBeam® Edge workflows.

Although residual rotational errors in the Halcyon™ TruPose workflow were slightly higher in pitch and roll compared with the TrueBeam® Edge cohort equipped with a 6DoF couch, the observed differences remained modest and clinically limited (Figure 6, Table 2). Importantly, mean and median residual rotational errors across all three rotational axes remained well below the 1° tolerance threshold. This is consistent with published data showing clinically relevant dosimetric impacts from rotational errors as small as $1\text{--}2^\circ$ in intracranial SRT, especially in single-isocenter multi-target treatments with off-isocenter lesions, supporting the clinical acceptability of the setup accuracy [6,7].

From a clinical perspective, yaw rotations are primarily driven by head lateral symmetry and thermoplastic mask conformity, both of which are effectively constrained by SGRT and TruPose-based setup and

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immobilization. Therefore, the absence of active yaw correction on Halcyon™ has a limited impact compared with pitch and roll, which are more sensitive to couch angulation.

Axis	Halcyon™ SGRT-only			Halcyon™ SGRT TruPose			TrueBeam® Edge		
	Mean ± SD	Median	Max	Mean ± SD	Median	Max	Mean ± SD	Median	Max
Pitch	1.0° ± 0.6°	0.9°	3.0°	0.8° ± 0.5°	0.7°	2.9°	0.3° ± 0.3°	0.2°	2.2°
Yaw	0.9° ± 0.5°	0.7°	2.8°	0.5° ± 0.3°	0.5°	2.0°	0.5° ± 0.4°	0.3°	3.3°
Roll	0.6° ± 0.4°	0.6°	2.4°	0.4° ± 0.3°	0.3°	2.0°	0.1° ± 0.2°	0.1°	1.3°

Table 2. Residual rotational errors (pitch, yaw and roll) for Halcyon™ SGRT-only, Halcyon™ TruPose and TrueBeam® Edge workflows, presented as mean ± standard deviation, median and maximum value.

Axis	SGRT-only vs SGRT TruPose (Mann-Whitney U)	SGRT TruPose vs TrueBeam® Edge (Mann-Whitney U)	SGRT TruPose vs TrueBeam® Edge (Student's t-test)
Pitch	0.047	0.000	0.001
Yaw	0.022	0.047	0.975
Roll	0.001	0.000	0.000

Table 3 - Pairwise statistical comparison of residual rotational errors between the Halcyon™ SGRT-only and Halcyon™ TruPose, and between the Halcyon™ TruPose and TrueBeam® Edge groups. p-values were obtained using the Mann-Whitney U test and Student's t-test.

When considering worst-case deviations, the integration of TruPose on Halcyon™ reduced maximum rotational errors compared with SGRT-only, particularly for yaw and roll, indicating improved control of outliers (Table 2), and TrueBeam® Edge demonstrated lower maximum pitch (2.2°) and roll (1.3°) errors, reflecting the benefit of active 6DoF correction in limiting extreme deviations. However, maximum yaw was higher in the TrueBeam® cohort (3.3°) compared with Halcyon™ TruPose (2.0°) and SGRT-only (2.8°), confirming that extreme yaw outliers are less dependent on couch-based correction and more influenced by immobilization and initial setup (Table 2).

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The Halcyon™ TruPose group also exhibited a reduced proportion of fractions exceeding angular tolerance thresholds, indicating improved setup consistency (Table 4). Among all analyzed fractions, residual rotational errors exceeding 2° occurred in 24.5% for the Halcyon™ SGRT-only cohort, while only 6.5% for the Halcyon™ TruPose cohort and 7.3% for the TrueBeam® Edge group (Table 4). These findings suggest that, although statistically significant differences were observed between the TrueBeam® Edge and Halcyon™ TruPose groups, they do not necessarily translate into clinically meaningful differences in this specific treatment context.

Angular tolerance	Halcyon™ SGRT-only	Halcyon™ SGRT TruPose	TrueBeam® Edge
> 2°	24.5%	6.5%	7.3%
> 1°	62.7%	29.5%	18.7%

Table 4 - Proportion of treatment fractions exceeding an angular tolerance of 1 and 2° for Halcyon™ SGRT-only, Halcyon™ TruPose and TrueBeam® Edge workflows.

Overall, these findings suggest that SGRT combined with open-face mask immobilization and TruPose can achieve positioning accuracy approaching that of more advanced 6DoF couch systems, provided that rigorous setup protocols are applied. However, larger residual pitch deviations were observed in the Halcyon cohort and motivated further investigation into potential contributing factors.

8.4 Image Frequency Analysis

Finally, the proportion of additional CBCT acquisitions per fraction significantly decreased with the combined use of SGRT and TruPose for Halcyon™—dropping from 18% for Halcyon™ SGRT-only cohort, to only 2% and 1% for Halcyon™ TruPose and TrueBeam® Edge workflows, respectively (Table 5). This highlights its potential for minimizing cumulative imaging dose.

Halcyon™ SGRT-only	Halcyon™ SGRT TruPose	TrueBeam® Edge
18%	2%	1%

Table 5 - Frequency of additional CBCT imaging for Halcyon™ SGRT-only, Halcyon™ TruPose and TrueBeam® Edge cohorts.

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8.5 Potential Sources of Pitch Variability

Several factors may contribute to the larger pitch deviations observed in the Halcyon cohort.

The open-mask configurations currently utilized within the Halcyon workflow may be more susceptible to inter-operator variability during thermoplastic molding. Although the combination of SGRT and open-face immobilization improves rotational setup consistency, its performance remains sensitive to mask design and surface visibility.

In particular, accurate mask fabrication is critical: maintaining correct forehead–chin alignment and ensuring sufficient mask openings over the forehead (for pitch assessment) and laterally (for roll) is essential for accurate detection by the ceiling-mounted cameras. These considerations underscore the importance of dedicated staff training and standardized mask fabrication protocols to ensure consistent and reproducible positioning accuracy.

Evaluation of enhanced fabrication standardization protocols is currently ongoing.

9 Discussion and Optimization Strategies

9.1 Workflow Efficiency

Although the SGRT–TruPose workflow introduces additional procedural steps compared with a conventional Halcyon setup, these steps represent a predictable and controllable time investment.

Preliminary observations indicate that manual rotational corrections typically require approximately 15 seconds.

Importantly, this modest fixed overhead may reduce the need for complete patient repositioning or repeated CBCT acquisitions when clinically significant rotational errors are identified on a 3-DOF platform.

9.2 Limitations

This study reports the experience of a single institution. Comparisons between the Halcyon and TrueBeam populations are potentially confounded by differences in immobilization systems, preventing definitive attribution of observed pitch discrepancies to any individual component of the workflow.

Prospective studies involving multi-institutional collaborations will be required to further characterize the accuracy, reproducibility, and efficiency of SGRT-guided rotational management strategies.

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10 Conclusion

The SGRT-guided TruPose workflow provides a feasible and reproducible strategy for managing rotational setup uncertainties during intracranial stereotactic treatments on Halcyon systems lacking native rotational correction capabilities.

Clinical implementation demonstrated encouraging agreement with CBCT-based assessments and residual rotational accuracies approaching those observed in a TrueBeam Edge reference cohort, particularly for yaw.

While optimization opportunities remain, notably regarding pitch reproducibility and immobilization standardization, the workflow offers an immediately deployable solution for institutions operating 3-DOF Halcyon platforms.

Furthermore, the recent introduction of a dedicated 6-DOF couch for Halcyon does not diminish the potential utility of SGRT-guided rotational management. In centers without access to a 6-DOF upgrade, TruPose provides a practical alternative for rotational correction. In centers equipped with native 6-DOF capabilities, SGRT-guided pre-positioning and post-imaging rotational reassessment may still contribute to improving setup efficiency and enhancing positional confidence.

Taken together, these findings suggest that SGRT-guided rotational management should be viewed not solely as a substitute for robotic 6-DOF technology, but rather as a complementary strategy capable of extending rotational management options across the diverse installed base of Halcyon and Ethos systems worldwide.

Disclosures

The ORLAM Group has worked with Vision RT to develop the SGRT solution for the Halcyon and is working with Standard Imaging to test the TruPose system on the Halcyon. The ORLAM Group is a designated referral center for Vision RT. The opinions expressed in this paper are those of the authors and do not reflect the official position of Vision RT, Standard Imaging, or the ORLAM Group institution.

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