Technical note

Commissioning and performance testing of the first prototype of AlignRT InBore™ a Halcyon™ and Ethos™-dedicated surface guided radiation therapy platform

Daniel Nguyen^{a,*}, Jad Farah^b, Nicolas Barbet^a, Mustapha Khodri^a

^a Department of Radiation Oncology, ORLAM group, 44 rue ambroise Paré, Mâcon, France

^b Vision RT Ltd., Dove House, Arcadia Avenue London, N3 2JU, United Kingdom

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ABSTRACT

Purpose: To commission and assess the performance of AlignRT InBore™, a Halcyon™ and Ethos™-dedicated Surface Guided Radiation Therapy (SGRT) platform which combines ceiling-mounted cameras for patient setup and bore-mounted cameras for in-bore tracking.

Methods: To check the potential impact of InBore™ cameras on dose delivery, 16 SRS, H&N, breast and pelvis patients' quality assurance (QA) treatment plans were measured with/without AlignRT InBore™ and using ArcCHECK® and SRS MapCHECK®. Impact on image quality was determined using Catphan® 540 phantom and considering all available MV and CBCT protocols (head, breast, chest and pelvis). The stability, accuracy and overall performance of AlignRT InBore™ was assessed using an MV Cube and anthropomorphic phantoms.

Results: Comparison of 2D dose distributions with/without AlignRT InBore™ showed no impact on treatment delivery for all 16 QA checks (p-value > 0.25). 2D and CBCT images showed no artefacts or change in the contrast-to-noise ratio, resolution and noise values measured with Catphan® 540. Anti-collision sensors were unaffected by the bore-mounted cameras. Additionally, AlignRT InBore™ cameras allowed for motion detection with sub-0.5 mm accuracy and sub-0.4 mm stability with surface coverage of >50 × 60 × 35 cc. Accurate transition (sub-0.3 mm) from virtual to treatment isocentres was achieved. Finally, Halcyon™ rotations during CBCT and beam delivery resulted in limited camera vibrations with translation uncertainty <0.5 mm in left-right and anterior-posterior directions and <0.1 mm in head-feet direction.

Conclusion: AlignRT InBore™ provides SGRT setup and intrafraction monitoring capabilities with a performance comparable to standard SGRT solutions while having no adverse effect on Halcyon™.

1. Introduction

Over the past decade, Surface Guided Radiation Therapy (SGRT) has been increasingly used to provide live and continuous supplementing information to Image-Guided Radiation Therapy (IGRT) at no additional X-ray exposure. Abundant literature indeed describes the benefits of SGRT proving faster and more accurate patient setup compared to tattoos, increased patient comfort and well-being post-radiotherapy through open-faced masks and tattoos avoidance, and reduced use of daily port/X-ray imaging [1–4]. In fact, recent studies have also shown SGRT (AlignRT, Vision RT, London, UK), ExacTrac (Brainlab, Munich, Germany), CBCT and Varian's Advanced Imaging techniques (Varian, Palo Alto, USA) to be fully interchangeable specifically for SRS

applications where sub-millimetric setup accuracy is required [5–7].

With such high accuracy and performance, SGRT has been leveraged across a broad range of clinical applications including breast (both in free breathing and deep inspiration breath hold - DIBH), stereotactic radiosurgery (SRS), stereotactic body radiation therapy (SBRT), head and neck, sarcomas, paediatrics, etc. [8–13]. Clinical outcomes with SGRT also proved to be equivalent to standard approaches. Namely, SGRT has been proved to provide accurate and reproducible breath hold for DIBH treatment of the left breast cancer [9] with sparing of the heart preventing any visible cardiac perfusion defects and wall motion defects on SPECT imaging 6-month post-radiotherapy [10]. Similarly, tumour control, survival rates and radiation toxicity proved to be similar in SGRT-driven SRS treatments compared to standard frame-based and

* Corresponding author.

E-mail address: nguyen.daniel@yahoo.fr (D. Nguyen).

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Fig. 1. AlignRT InBore™ installed on Halcyon™ showing standard three ceiling-mounted cameras for patient setup and the new InBore™ system for intra-fraction motion tracking (left). View of the new InBore™ solution tracking the MV Cube at treatment isocentre (right).

gamma knife approaches [12,13].

However, for closed bore Linacs such as Halcyon™ and Ethos™ (Varian, Palo Alto, USA) or Tomotherapy (Accuray, Sunnyvale, USA), the use of ceiling mounted SGRT solutions remains scarce and limited to improving setup accuracy with the cameras being unable to track the patient motion inside the bore due to optical line of sight limitations [14,15]. This work hence tests the suitability and performance of the first prototype of AlignRT InBore™, a new Halcyon™ and Ethos™ dedicated SGRT solution from Vision RT (Vision RT Ltd., London, UK) capable of tracking patient motion during treatment delivery.

2. Materials and methods

2.1. The AlignRT InBore™ prototype

AlignRT InBore™ is the new Halcyon™ and Ethos™ dedicated SGRT platform (Vision RT Ltd., London, UK) combining ceiling-mounted cameras for patient setup and bore-mounted cameras for in-bore monitoring. The new InBore™ solution uses miniature stereo vision cameras together with multiple infrared projectors to optically track the patient surface in 3D. For this first prototype, the 1 m diameter ring supporting the cameras is made of carbon fibre material with 17 cm maximum depth and 3 cm thickness and a total weight of ~ 2.7 kg. Rubber friction mounts around the ring reduce vibrations and apply outward gentle pressure on the Halcyon™ bore to secure AlignRT InBore™ inside the bore while avoiding any abrasive fixation to the Halcyon™ machine. The InBore™ ring is installed mid-way between virtual (i.e. bore lasers) and treatment isocentres where the three arch parts/components are assembled with a simple locking clip system (cf.

Fig. 1). The distance between the InBore™ ring border and the widest treatment field edge was about 6 cm.

2.2. Commissioning

To confirm that AlignRT InBore™ system does not affect beam delivery, the widest possible treatment field (28 cm wide in the longitudinal plane) was delivered with/without the ring in place. Dose distributions were acquired with the EPID and analysed using Varian's Portal Dosimetry software v.15.6 (Varian, Palo Alto, USA).

Additionally, patient QA dosimetry checks were performed with/without AlignRT InBore™ and using ArcCHECK® and SNC Patient™ v.8.3 (Sun Nuclear, Melbourne, USA) for a total of 11 randomly selected patients simulating breast (2 IMRT and 3 VMAT), H&N (2 VMAT) and pelvis (4 VMAT) treatment sites. A local dose distribution analysis was performed to compare acquisitions with/without the InBore™ system with 0.1% and 0.5% dose difference criteria with 5% threshold since ArcCHECK® and SNC patient v.8.3 do not allow for gamma index analysis comparing two measurements. Additionally, 5 SRS patients were randomly selected, and their QA dosimetry checks performed using SRS MapCHECK® inserted into the StereoPHAN and SNC patient v.8.3 (Sun Nuclear, Melbourne, USA). In this case, a global gamma index analysis was performed with 0.5% – 0.5 mm and 1% – 1 mm criteria comparing measurements with/without AlignRT InBore™ to Eclipse (Varian, Palo Alto, USA) Treatment Planning System (TPS) plans since SRS MapCHECK® and SNC Patient™ v.8.3 do not allow for direct comparison of two measurements. Selected patients and plan parameters are given in Table 1.

Next, CBCT image quality was visually determined by the presence/

Table 1

Patient selection and plan parameters for the 16 patient QAs considered in this study.

Patient number	Site	Plan parameters	Patient number	Site	Plan parameters
1	Dynamic IMRT Breast	4 fields, 6 MV FFF, 800 MU/min, 592 MUs	9	VMAT Pelvis	3 full arcs, 6 MV FFF, 800 MU/min, 1062 MUs
2	Dynamic IMRT Breast	3 fields, 6 MV FFF, 800 MU/min, 566 MUs	10	VMAT Pelvis	4 full arcs, 6 MV FFF, 800 MU/min, 999 MUs
3	VMAT Breast + lymph nodes	4 partial arcs, 6 MV FFF, 800 MU/min, 1245 MUs	11	VMAT Pelvis	4 full arcs, 6 MV FFF, 800 MU/min, 884 MUs
4	VMAT Breast + lymph nodes	4 partial arcs, 6 MV FFF, 800 MU/min, 1350 MUs	12	SRS	4 full arcs, 6 MV FFF, 800 MU/min, 3028 MUs, target volume = 11.83 cc
5	VMAT Breast + lymph nodes	4 partial arcs, 6 MV FFF, 800 MU/min, 1746 MUs	13	SRS	4 full arcs, 6 MV FFF, 800 MU/min, 2738 MUs, target volume = 1.79 cc
6	VMAT H&N	3 partial arcs, 6 MV FFF, 800 MU/min, 443 MUs	14	SRS	4 full arcs, 6 MV FFF, 800 MU/min, 2449 MUs, target volume = 1.22 cc
7	VMAT H&N	4 partial arcs, 6 MV FFF, 800 MU/min, 820 MUs	15	SRS	4 full arcs, 6 MV FFF, 800 MU/min, 2442 MUs, target volume = 0.06 cc
8	VMAT Pelvis	3 full arcs, 6 MV FFF, 800 MU/min, 795 MUs	16	SRS	4 full arcs, 6 MV FFF, 800 MU/min, 1929 MUs, target volume = 0.01 cc

absence of artefacts as well as using the Catphan® 540 phantom (The Phantom Laboratory Inc., Salem NY, USA). ARTISCAN QA software v4.16 (AQUILAB, Loos, France) was used to determine contrast, resolution and noise in the set of images acquired with/without AlignRT InBore™. Default acquisition parameters for all available kV-CBCT protocols were considered simulating head, breast, thorax and pelvis localisations as well as low and high definition MV-CBCT. MV image quality with/without AlignRT InBore™ was also verified using the EPID QC phantom (PTW, Freiburg, Germany) and ARTISCAN QA software v4.16.

Statistical analysis was also performed using Wilcoxon non-parametric tests to investigate any significant difference on dose delivery and image quality with/without AlignRT InBore™.

Finally, the sensitivity of the two anti-collision sensors installed at the rear of the Halcyon™ was also checked with/without the ring in place with a NK-500 force gauge (Zhejiang Beilong Tool Co. Ltd., Zhejiang, China) and while applying gradual pressure to the bore at 9 different positions including those overlaying the sensors. Each measurement was repeated 3 times for consistency and the average $\pm$ standard deviation reported.

2.3. Performance testing

The stability of InBore™ cameras was determined when

Fig. 2. Left: ArcCHECK® local 2D dose distribution comparison for 11 patients considering 0.1% criteria (dots) and 0.5% criteria (triangles). Right: SRS MapCHECK® global gamma index analysis for 5 patients comparing TPS distributions vs. measurements with (full symbols) and without (empty symbols) AlignRT InBore™ considering 0.5%-0.5 mm criteria (dots) and 1%-1mm criteria (triangles).

continuously monitoring for ~ 30 min the MV Cube (Vision RT Ltd., London, UK) and measuring the variability of real time delta (RTD) which report the translations, rotations and magnitude of shifts. This measured any thermal drift, a previously identified uncertainty on SGRT solutions.⁷

The accuracy of the InBore™ cameras in detecting patient motion was also investigated using the dedicated MV Cube containing 5 radio-opaque spheres with known positions inside the cube. Known couch shifts (from 1 mm and up to 1 cm) were next applied in all translational directions and MV images were then acquired and the position of the spheres was analysed and compared to SGRT-provided RTD values.

The correspondence between ceiling mounted cameras and InBore™ cameras is established during calibration (plate or MV cube) allowing for accurate transition from virtual isocentre (i.e. bore lasers), where the patient is setup, to treatment isocentre. To test the robustness of this co-calibration, the MV Cube (Vision RT Ltd., London, UK) was aligned to sub 0.2 mm/0.1° accuracy (for all 7 variables of RTDs) using the ceiling-mounted camera and then automatically moved inside the bore to treatment isocentre using Halcyon™-specific delta couch shifts (57.64 cm in head-feet, -3.3 mm in vertical and 0.6 mm in lateral directions). InBore™ monitoring was next activated and RTDs were noted and compared to ceiling-mounted values. MV images at 0°, 90°, 180° and 270° were also acquired and SGRT was matched to EPID images. The MV Cube was next shifted by 1, 3, 5 and 10 mm in each of the translational directions successively and RTDs were noted and matched to MV images and table shifts. Additionally, to investigate any couch sag, extra weight (20, 40, 60 and 80 kg) was added on the couch, which was also laterally shifted from isocentre position by 0, 5, 10 and 15 cm to replicate breast patient treatments.

Finally, the mechanical stability of the ring was assessed by determining whether the rotation of the Halcyon™ gantry during CBCT imaging and/or beam delivery could create an offset between treatment isocentre and camera isocentre. To perform this study, the ceiling mounted cameras were first used to track different markers installed on the ring. Next, the InBore™ camera system was used to continuously

Fig. 3. Comparison of noise (left) and resolution (right) with (full symbols) vs. without (empty symbols) AlignRT InBore™ using Catphan® 540 and considering all clinical CBCT protocols including head (diamonds), breast (circles), chest (cubes) and pelvis (triangles).

monitor the ArcCHECK® throughout the delivery of multiple CBCT sequences (up to 10 cycles repeated) and the 11 patient QA tests (see previous section).

3. Results and discussions

3.1. Beam delivery

With the widest possible treatment field ($28 \times 28 \text{ cm}^2$) delivered with/without AlignRT InBore™, $\gamma_{\text{global}} = 100\%$ (respectively $\gamma_{\text{local}} = 100\%$) for the 1% – 1 mm and $\gamma_{\text{global}} = 98.1\%$ (respectively $\gamma_{\text{local}} = 96.9\%$) for 0.5% – 0.5 mm criteria showing no clinically relevant dosimetric impact. This result was further confirmed with 5 breast,

2H&N and 4 pelvis patient QAs with measured 2D dose distributions strongly matching for 0.1% and 0.5% dose criteria (cf. Fig. 2 left). The global gamma index analysis comparing planned and measured dose distributions for the 5 SRS patients (cf. Fig. 2 right) also show no significant difference with/without AlignRT InBore™ ($p > 0.25$ for both 0.5% – 0.5 mm and 1% – 1 mm criteria).

3.2. Image quality

No artefact was observed on the MV, kV-CBCT and MVCT images with the InBore™ ring installed inside the Halcyon™ bore. Image quality assessed with Catphan® 540 phantom and with EPID QC phantom showed no statistically significant differences on contrast-to-

Table 2

Results of the statistical analysis (p -values) comparing image quality with/without AlignRT InBore™ using Catphan® 540 and considering clinically available CBCT and MVCT acquisition protocols.

CBCT	Head	Chest	Breast	Pelvis	MVCT	High Quality	Low Quality
Resolution	0.84	0.16	0.09	0.69	Resolution	0.16	0.69
CNR	1	0.56	0.44	0.68	CNR	0.31	0.84
Noise	0.31	0.84	0.56	0.09	Noise	0.44	0.31

Fig. 4. System stability test showing the variation of translations (left) and rotations (right) for ~ 30 min of monitoring.

noise ratio (CNR), resolution or noise values (cf. Fig. 3 and Table 2).

3.3. Anti-collision sensors

When installing the InBore™ ring, anti-collision sensors detected the pressure induced by the ring sliding inside the bore. As soon as the cameras were in position, the pressure was released, and with no detected pressure the anti-collision sensors authorized beam delivery. Additionally, the presence of the ring did not affect the sensitivity of

anti-collision sensors as the trigger value with/without AlignRT InBore™ did not vary by >1.5 N (which is roughly equivalent to the reading/measurement uncertainty estimated from the standard deviation of the repeatability test). One should however note a noticeable difference between left and right sensors with the former being almost triggered at half the pressure.

Fig. 5. Top: Variation of x, y and z RTDs (mm) analysed on over 1000 images recorded by the ceiling-mounted cameras when tracking the ring vibrations while running repeated CBCTs. Bottom: Variation of translations and rotations recorded by the InBore™ cameras when tracking ring vibrations during treatment fields and CBCTs.

3.4. Camera performance

Accuracy of the InBore™ system proved to remain within 0.1 mm when tested using the MV Cube and with known applied shifts ranging from 1 mm to 1 cm in all translational directions.

Stability of the system when continuously monitoring the MV Cube for ~30 min also showed limited variability of the RTDs in time (sub-0.3 mm and 0.2°) with no visible thermal drift (cf. Fig. 4).

Additionally, with the current AlignRT software version (v.5.1) the new InBore™ cameras proved to have similar performance compared to the standard ceiling-mounted cameras with a frame rate of 3–5 fps and a surface resolution of 10 pixels/vertex for breast anatomical site.

3.5. Transition from virtual to treatment isocentre

Tests with the MV Cube proved the cross calibration of ceiling and

InBore™ cameras to be efficient and robust enabling accurate transition from virtual to treatment isocentre with RTDs within 0.3 mm. However, when matching camera isocentre (both ceiling and InBore™) to the radiographic isocentre, higher uncertainties (up to 1.2 mm) were obtained with plate calibration. This is due to possible laser motion/misalignments and the subjective nature of plate positioning further supporting the need for MV Cube calibration for Halcyon™. Once this advanced calibration is performed, the InBore system proved to be capable of accurately computing any lateral and longitudinal shifts with sub-0.2 mm accuracy as confirmed on the portal images. Finally, gradually adding weight on the couch top (up to 80 Kg) showed a slight sag in vertical (up to 1.5 mm) and longitudinal directions (within 1 mm). These shifts registered on the InBore™ cameras were also confirmed by the CBCT images.

3.6. Stability to vibrations

Halcyon™ rotations during CBCT and beam delivery resulted in limited camera vibrations with translation uncertainty <0.5 mm in left–right and anterior–posterior directions and <0.1 mm in head–feet direction as detected by the ceiling-mounted cameras (cf. Fig. 5 top). The InBore™ cameras also proved to be unaffected by gantry rotations during CBCT or beam delivery (cf. Fig. 5 bottom) with sub-0.4 mm/0.2° variation of any translation/rotation computed during the monitoring.

4. Discussion

AlignRT InBore™ is a hybrid solution combining standard ceiling-mounted cameras with new technology for InBore™ cameras. The system is easy to install and re-install simply requiring the ring to be assembled and slid into the Halcyon™ bore.

Firstly, it was possible to confirm that the InBore™ cameras did not have any significant impact on dose delivery and image quality. From Fig. 4, one could note markedly poorer dose delivery for patient #7 compared to the other patients. This is however independent from the presence/absence of the InBore™ system and is mainly due to the 10% cut-off threshold set for the analysis which tends to overestimate the disagreement in the low dose area of this ipsilateral H&N IMRT treatment.

Secondly, when comparing the performance of the standard ceiling-mounted cameras to the new InBore™ system, similar accuracy (sub-0.5 mm) was obtained. The accuracy of the InBore™ system in quantifying rotational shifts could not be fully benchmarked since the Halcyon™ couch does not allow for applying rotations; this requires further investigations using high precision rotating test objects. Additionally, InBore™ cameras showed improved stability (sub-0.3 mm and 0.2° variability of RTDs for 30 min of monitoring) compared to the ceiling system where a 0.4 mm thermal drift was previously reported [7]. It is worth noting that longitudinal and rotation displacements have increased variance compared to the other dimensions (cf. Fig. 4). This is probably due to small imperfections in surface reconstruction when monitoring the cube and will be further investigated. Since frame rate and surface resolution are dependent on the software version used, equivalent performance was observed for both systems (2–5 fps and); this will improve with the new software release (Advance™ v. 6.2). Ceiling cameras have a wider field of view (100 × 65 × 35 cc) when compared to the InBore™ cameras which are much closer to the isocentre and offer a tracking surface coverage of >50 × 60 × 35 cc. This was nonetheless deemed sufficient for all clinical applications although an increased lateral coverage would be beneficial for breast sites to monitor contralateral breast and arm movement during beam delivery. The current software version however is not able to run ceiling-mounted cameras and InBore™ units simultaneously which in this prototype form makes the workflow sub-optimal.

As for the camera cross-calibration process, MV Cube calibration should be privileged to match the camera isocentres (ceiling and

InBore™) to Linac isocentre especially since no field light or in-bore lasers are available on Halcyon™. Additionally, it was noticed that anti-collision tests performed by the radiation therapists as part of the daily quality assurance program of the Halcyon™ could have an impact on system performance causing regular failure of InBore™ cameras' dailyQA. Indeed, the Halcyon™ bore and structure supported by springs may be shifted by up to 2–3 mm from their original position after these tests; for the InBore™ cameras to have sub-millimetric precision, these should also be calibrated on daily basis.

Additionally, the new speckle pattern projector installed on the InBore™ system has a wavelength of 850 nm which makes it totally invisible to the human eyes and to the two surveillance CCTV cameras installed inside the Halcyon™ bunker. However, Varian's couch-mounted camera was able to detect the speckle pattern flashing on the patient skin, likely due to the absence of a filter in that camera. While some therapists deemed this visualisation necessary and reassuring since it proved the InBore™ monitoring cameras were operational, others preferred the pattern to remain completely invisible.

The current solution also does not offer automatic beam hold as Halcyon™ does not currently support a Motion Management Interface (MMI). Instead, the radiation therapists need to be constantly monitoring the AlignRT screen to manually hold the beam if the patient moves out of tolerance.

Finally, while the prototype showed some limited collision risks with the patient/couch, enhancements in design are expected in the final product (thinner model). Other actions to reduce any collision risks include increasing security margins during treatment planning and setting up the patient with lateral shift on the couch; this is particularly relevant for heavy patients.

5. Conclusion

This work tests the suitability and performance of the first prototype of AlignRT InBore™, a new Halcyon™ and Ethos™-dedicated SGRT solution capable of tracking patient motion during treatment delivery. The study proved AlignRT InBore™ to have no adverse effect on Halcyon™ beam delivery and image quality with an overall performance similar to the standard SGRT solution. SGRT on Halcyon™ is particularly relevant for patient setup to correct for gross rotational shifts since post-CBCT, the user can only correct for translational shifts (3 DoF couch). Additionally, offering the ability to track inside the bore and monitor patient motion during beam delivery (and CBCT imaging) with sub-millimetric precision will greatly improve treatment accuracy and shall allow for advanced treatment techniques such as DIBH to be performed on Halcyon™. Several software enhancements as well as some improvements to the overall product design are expected to render this solution fully compatible with routine clinic.

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