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Reproducibility of Deep-Inspiration Breath Hold treatments on Halcyon™ performed using the first clinical version of AlignRT InBore™: Results of CYBORE study

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ABSTRACT

Background and purpose: To investigate the reproducibility of deep-inspiration breath hold (DIBH) breast cancer treatments on Halcyon™ performed using the first clinical version of AlignRT InBore™ (Vision RT Ltd., London, UK), a Halcyon's SGRT dedicated solution.
Materials and methods: The ease and feasibility of DIBH treatments was retrospectively investigated for the initial 22 left breast cancer patients treated on Halcyon™ using AlignRT InBore™. Setup time, Cone beam computed tomography (CBCT) imaging and analysis time as well as overall treatment time were recorded. Online and offline review of CBCT images was undertaken to verify the compliance of breast, heart, spine, sternum and diaphragmatic domes positions.
Results: Mean duration of patient setup, CBCT analysis and overall treatment time were 4 min, 1.1 min and 14 min respectively. Online review of 520 CBCT acquisitions by therapists showed minimal positioning shifts with AlignRT InBore™ guidance with mean value of vertical, longitudinal, and lateral shifts of 1.7 mm, −1.7 mm, and −0.2 mm respectively. Meanwhile, offline review of 115 CBCTs by the radiation oncologist, showed reproducible breath hold (BH) with average deviation of breast, heart, spine, sternum and diaphragmatic domes respectively within 2.4 mm, 2.9 mm, 3.3 mm, 3.2 mm and 4.5 mm in magnitude.
Conclusion: AlignRT InBore™ allows for accurate and reproducible DIBH on Halcyon™ with breast and heart organs' positions within 3 mm in magnitude of expected position and fully compliant with planning margins (5 mm anisotropic CTV-PTV margins).

Introduction

External beam radiotherapy represents one of the most common and efficient treatment techniques for breast cancer [1]. However, radiation-induced toxicities represent a major concern for left-breast cancer patients. Indeed, Darby et al. demonstrated the rates of major coronary events (ischemic heart disease) to increase linearly with the mean heart dose by 7.4% per gray with no apparent threshold [2]. Additionally, Jacobse et al. showed that the excess rate ratio of myocardial infarction increased for younger women (<45 years-old) rising to 24.2% per Gy [3]. Lastly, Jacob et al. concluded that mean heart dose (MHD) is not enough to predict with confidence individual patient dose to the left anterior descending artery (LAD) which could be damaged by radiation and lead to severe left ventricle impairment and congestive heart failure [4]. As such, it is essential to reduce the radiation exposure of the heart and its sub-structures for every left breast cancer patient treated with radiotherapy.

To achieve this goal, various approaches have been widely used including intensity-modulated radiation therapy (IMRT) [5], volumetric modulated arc therapy (VMAT) [6], prone breast radiation therapy [7], lateral decubitus positioning [8], proton therapy [9] and the deep-inspiration breath hold technique (DIBH) [10]. These approaches can be used separately or in conjunction (ex. prone position and DIBH) [11].

DIBH can be moderate (mDIBH) i.e. controlled with a spirometer

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such as the Active Breathing Control device (ABC) (Elekta, Stockholm, Sweden) [12], or voluntary (vDIBH or DIBH) i.e. relying on patient's ability to hold their breath at a specific position in the breathing cycle. When compared to mDIBH, DIBH was found to offer faster simulation and daily setup times, greater patient and therapists' satisfaction, better patient toleration as well as lower costs [10]. Two of the most common guidance methods for DIBH are the RPM - Real-time Position Management (Varian Medical Systems, Palo Alto, USA) and SGRT - surface guided radiation therapy [13]. SGRT has been proven to offer superior correlation with the actual target positioning compared to RPM [14] and ABC while also detecting unexpected patient motion during BH undetectable by the air volume-based system [15].

One of the main challenges in implementing DIBH treatments is to ensure BH reproducibility while confirming heart position and organs-at-risk (OAR) dose sparing. Abundant literature proved the reproducibility of breast positioning in DIBH using typical 2D X-ray imaging such megavoltage (MV) planar imaging, cine fluoroscopy and kilovoltage (kV) -orthogonal images [16–20]. However, such imaging modalities suffer from a limited contrast and restrained field of view (FOV) which prevent the full analysis of heart position and of relevant critical structures such as the LAD, diaphragmatic domes, spine, sternum, etc. Instead, wider imaging FOV offered by CBCT acquisitions have been considered in a more recent study which showed moderate correlation between surface and heart setup errors in DIBH [21]. One major limitation preventing the systematic use of CBCT acquisitions to confirm reproducible DIBH is imaging dose and acquisition time which generally exceeding 30/40 s even when considering partial arc (up to 210°) CBCT imaging. Fortunately, recent O-ring type linear accelerators such as the Halcyon™ (Varian Medical Systems, Palo Alto, USA) offer fast imaging times (within 17 s) compatible with a single BH and a wide-enough FOV (a longitudinal scan range of 24.5 cm) to allow for the validation of target and OAR positioning in DIBH. While standard SGRT systems cannot track intra-fractional surface motion inside the bore even with adjusted central camera positioning [22], we used and evaluated here the new AlignRT InBore™ solution dedicated for closed-bore linacs [23].

The present paper investigates the reproducibility of breast, heart, diaphragmatic domes, spine, and sternum positioning during AlignRT InBore™-guided DIBH treatments performed on Halcyon™. This study was named CYBORE study.

Materials and methods

Patient selection and prescription

Left breast cancer patients able to hold their breath for a minimum of 20 s, roughly corresponding to the duration of the CBCT acquisition on Halcyon™, were considered eligible for DIBH. Patients' informed consent was obtained during the radiation oncologist consultation. Data of the initial 22 patients treated between November 19th 2020 and March 15th 2021 with AlignRT InBore™ were analyzed. Organ delineation was performed following recommendations of the Radiation Therapy Oncology Group (rtog.org) and commonly used atlas [24,25]. Typical prescription was in 25 fractions of 50 Gy or breast/chest wall and 47.5 Gy or supraclavicular (SCL)/axillary (Ax) ± internal mammary chain (IMC). The radiotherapy planning target volume (PTV) encloses the clinical target volume (CTV) with 5 mm anisotropic margins. For breast/chest wall alone treatments, sliding windows IMRT treatment planning (with 4 to 6 fields) was conducted using Eclipse v. 15.6 (Varian Medical Systems, Palo Alto, USA) while for breast/chest wall with SCL/Ax ± IMC, Volumetric Modulated Arc Therapy (VMAT) deliveries (with 4 partials arcs) were planned using Raystation v10B (RaySearch Laboratories AB, Stockholm, SE).

Patient coaching and computed tomography (CT) simulations

Prior to acquiring the CT scans, SGRT-based coaching was performed in the CT room with the patient set in the supine position over a 5° inclined BreastBoard LX™ (Macromedics, ML Moordrecht, NL) with both arms raised above the head. A single SGRT camera installed at couch feet was used to acquire a BH reference surface. Visual coaching of the patient using the RTC - Real Time Coach™ (Vision RT Ltd., London, UK) was considered to ease and improve the reproducibility of BH for all patients [26]. The patient was instructed to hold his breath to a level insuring a comfortable and reproducible BH without any minimal chest elevation threshold/range. Subsequently, two CT scan acquisitions, one in free-breathing (FB) and the other in breath hold (BH) with the SGRT, were performed with 2 mm slice thickness on a 64-slice Aquillon LB™ CT (Canon Medical Systems, Ōtawara, JP) using standard thoracic CT acquisition protocols. After CT simulation, the patient was encouraged to practice DIBH at home as this has been shown to result in more relaxed patients and to improve BH reproducibility [18].

Setup and treatment workflows

AlignRT InBore™ is an SGRT solution for use with Halcyon™ and Ethos™ linear accelerators. It combines the benefits of ceiling mounted AlignRT Advance camera pods for patient setup, with miniaturized SGRT ring camera system mounted within intra-fraction monitoring. It was used for patient setup and DIBH guidance during CBCT and beam delivery. Standard AlignRT ceiling-mounted cameras were used for patient setup at the virtual isocenter and AlignRT InBore™ ring-mounted cameras were utilized for intra-fraction motion monitoring once the patient was in treatment position (distances between both isocenters in.

Head-Feet/Posterior-Anterior/Right-Left directions of respectively +576.4/-3.3/0.6 mm) [23]. Consistent visual coaching was achieved using the RTC paired with both the ceiling cameras and the InBore™ ring. SGRT setup thresholds were set to 2 mm in the vertical direction and 3 mm and 3° for the remaining translations and rotations respectively. Patient setup relied on a Region of Interest (ROI) covering the treated breast (and supra-clavicular area), sternum and extended to the contralateral breast. Meanwhile, intra-fraction motion monitoring involved a ROI exclusively overlapping the treated breast to account for the narrower FOV for the InBore™ cameras. These ROIs are used by AlignRT with the rigid registration algorithm to match, following an iterative closest point match process, the current patient surface to the reference surface – typically the external contour from the DICOM-RT Structure Set.

Setup and treatment duration of DIBH

To determine the feasibility and clinical compatibility of DIBH, comprehensive data collection and analysis was performed. Firstly, session duration and CBCT shifts were retrospectively collected using Aria® oncology information system (Varian Medical Systems, Palo Alto, USA). Secondly, setup time, CBCT analysis time, number and duration of BH required for treatment delivery were manually recorded by the radiation therapists at the treatment console. Additionally, treatment reports automatically generated by AlignRT InBore™ in ".csv" format were retrospectively analyzed using a Python script [27] to compute monitoring time including setup, CBCT imaging and analysis, treatment duration as well as the number and duration of each treatment BH.

Online and offline review of CBCT images

Daily online soft tissue matching of CBCT acquisitions to planning CT images was performed by one of the therapists (all with >10 years' experience) operating the Halcyon™ machine. CBCT shifts applied by the therapist were retrospectively collected to determine the reproducibility of DIBH. Additionally, a retrospective offline review of CBCT

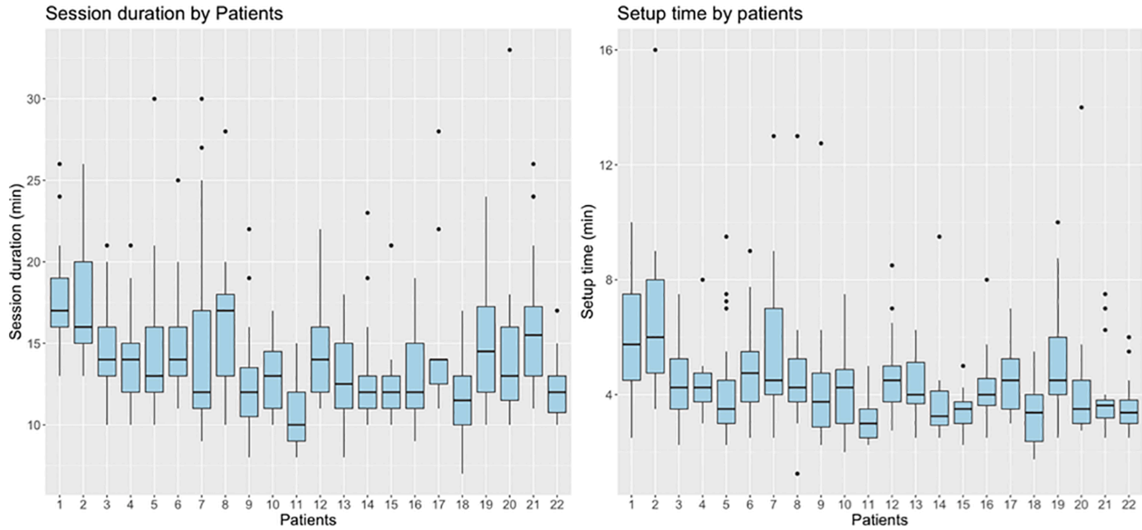

Fig. 1. Boxplot representation of session duration (left) and setup time (right) for all 22 patients.

images was undertaken by the senior physician leading this study to individually verify the compliance of breast, heart, spine, sternum and diaphragmatic domes positions. For each of the 22 patients enrolled in this study, a minimum of one set of CBCT images per week was randomly selected and analyzed. CBCT images were registered to planning CT data and vertical, longitudinal and lateral shifts were manually reported into a dedicated registry. For diaphragmatic domes, it is worth noting that only longitudinal shifts were computed while setting the sagittal and axial sections to the isocenter plan.

Statistical analysis

Quantitative variables were expressed by the mean and standard deviation. For non-normal distributions, the median was included. Qualitative variables were expressed by size and percentages.

Linear mixed models were also used to analyze the evolution of setup time and treatment duration as a function of treatment fractions (Patients' learning curve) and time (Therapists' learning curve).

For all statistical analyses, a p-value lower than 0.05 was considered as statistically significant. 95% confidence intervals (CI) were calculated with a bootstrap method to analyze the accuracy of the results.

Statistical analyses were performed using Rstudio v 1.2.5001 (https://www.rstudio.com/, Boston, USA).

Results

Patients characteristics

The patients had an average age of 63 years, height of 1.60 m, weight of 63 kg and BMI of 24.6. Among this population, 23% were treated for

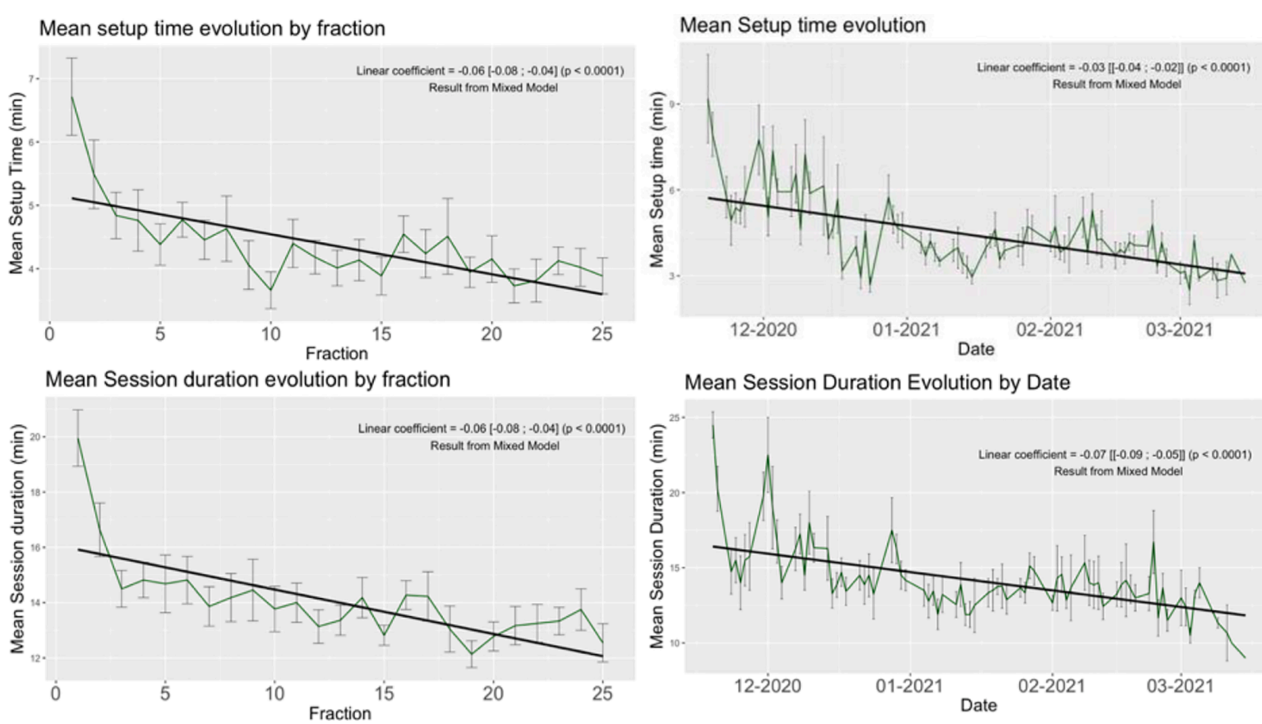

Fig. 2. Mean setup time (up) and session duration (down) as a function of treatment fraction (left) and date (right).

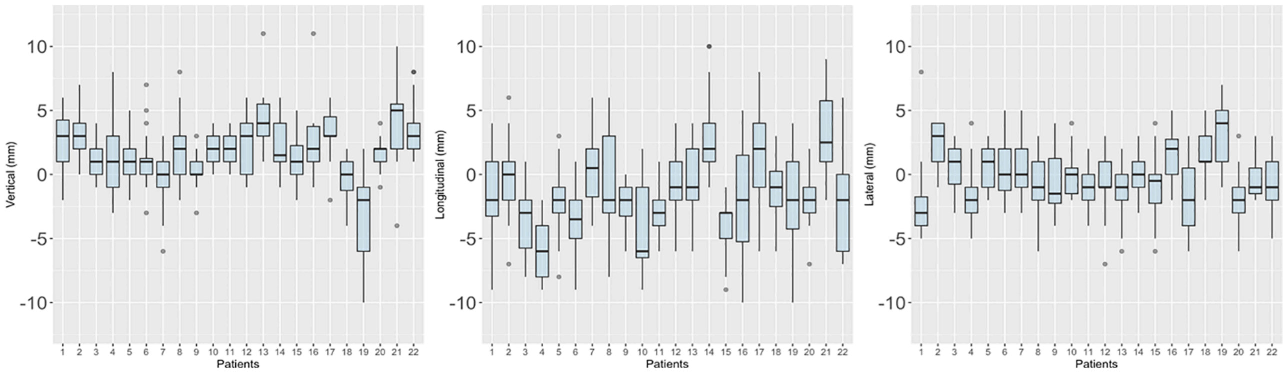

Fig. 3. Boxplot representation of CBCT shifts for all 22 patients in vertical (left), longitudinal (middle), and lateral directions (right).

Table 1
Mean ± standard deviation, Median (Q1–Q3) and Magnitude of CBCT shifts per organ following offline review of 115 CBCT images.

Organ	Translation [cm]	Mean ± standard deviation [mm]	Median (Q1–Q3) [mm]	Mean Magnitude ± standard deviation [mm]	Median (Q1–Q3) Magnitude [mm]
Breast	Vertical	−0.7 ± 1.9	0 (−2.0–0.0)	2.3 ± 2.4	2.0 (0.0–3.5)
	Longitudinal	0.2 ± 2.3	0 (0.0–0.0)		
	Lateral	0.1 ± 1.5	0 (0.0–1.0)		
Heart	Vertical	−0.2 ± 2.0	0 (−1.0–1.0)	2.9 ± 2.0	2.3 (1.4–4.2)
	Longitudinal	−0.4 ± 2.3	0 (−1.0–0.0)		
	Lateral	0.1 ± 1.8	0 (−1.0–1.0)		
Diaphragmatic Domes	Longitudinal	−2.5 ± 5.7	−2.0 (−6.0–1.0)	4.5 ± 4.0	4.0 (1.0–7.0)
Spine	Vertical	0.5 ± 2.0	0 (−1.0–1.0)	3.3 ± 2.2	3.0 (2.0–4.2)
	Longitudinal	−0.1 ± 2.8	0 (−1.0–1.0)		
	Lateral	0.5 ± 1.9	0 (0.0–1.0)		
Sternum	Vertical	−0.1 ± 1.9	0 (−1.0–1.0)	3.2 ± 2.4	2.4 (1.4–4.6)
	Longitudinal	−0.4 ± 3.1	0 (−2.0–1.0)		
	Lateral	0.0 ± 1.8	0 (−1.0–1.0)		
All	Vertical	−0.5 ± 2.4	−0.5 (−2.0–1.0)	3.4 ± 2.5	3.0 (1.4–4.6)
	Longitudinal	0.4 ± 2.9	0 (−1.0–1.8)		
	Lateral	0.3 ± 1.7	0 (−1.0–1.0)		

chest wall cancer and 77% of the treatments included supraclavicular/axillary lymph nodes (SCL/Ax) ± IMC.

Setup, CBCT imaging and treatment times

Fig. 1 represents the session duration and setup time for the 22 patients enrolled in this study respectively retrieved from ARIA OIS or manually recorded by the therapists. Mean ± standard deviation for patient setup time, CBCT analysis and overall treatment time were 4.5 ± 2.0 min, 1.1 ± 0.5 min and 14.2 ± 3.8 min respectively. Meanwhile, values extracted from the SGRT treatment reports show that 4 ± 1 treatment BHs of 27 ± 9 s each were typically required to deliver the treatment both in IMRT and VMAT with an average monitoring time of 2.7 ± 0.6 min with ceiling cameras and of 7.2 ± 1.0 min with InBore™ cameras (cf. Appendix A).

Fig. 2 represents the evolution of setup time and session duration over the treatment fractions and treatment dates. The linear mixed model coefficient was of −0.06 min (95% CI: [−0.08–−0.04], $p < 0.0001$) for the mean setup time evolution by fraction and −0.03 min (95% CI: [−0.04–−0.02], $p < 0.0001$) by treatment date. Additionally, the linear coefficient was equal to −0.06 min (95% CI: [−0.08–−0.04], $p < 0.0001$) for the mean session duration evolution as a function of treatment fraction and −0.07 min (95% CI: [−0.09–−0.05], $p < 0.0001$) for the mean session duration evolution as a function of treatment date.

Online review of CBCT images

Fig. 3 documents the distribution of CBCT shifts per patient based on the online registration performed by the therapist during treatment sessions. Mean ± standard deviation of vertical, longitudinal, lateral and magnitude shifts across all patients and treatment sessions were of 1.7 ± 2.5 mm, −1.7 ± 3.8 mm, −0.2 ± 2.5 mm and 5.2 ± 2.5 mm respectively. Median (Q1- Q3) values were respectively of 2 (0–3) mm in vertical, −2 (−4–0) mm in longitudinal, 0 (−2–1) mm in lateral and 4.5 (3.3–6.7) mm in magnitude. Absolute shifts in vertical, longitudinal, lateral and magnitude directions were of 2.4 ± 1.9 mm, 3.3 ± 2.6 mm, 2.0 ± 1.5 mm and 5.2 ± 2.5 mm respectively.

Offline review of CBCT images

Table 1 presents the average ± standard deviation shift computed in each direction and in magnitude (root mean square of the three translations) individually assessed for each organ. Mean ± standard deviation of absolute unidirectional translational shifts required to align the breast, heart, spine, sternum and diaphragmatic domes individually were found to remain within 1.1 ± 1.6 mm, 1.3 ± 1.5 mm, 1.5 ± 1.7 mm, 1.5 ± 1.8 mm and 4.5 ± 4.0 mm respectively. Median (Q1-Q3) values remained within 0.0 (0.0–2.0) mm for the breast, 1.0 (0.0–2.0) mm for the heart, spine and sternum, and within 4.0 (1.0–7.0) mm for the diaphragmatic domes. The breast and heart structures remain within 3.5 mm (in magnitude) of the expected position proving reproducible DIBH and compliance with local planning margins (anisotropic 5 mm CTV-PTV margins) while offering efficient heart sparing.

Discussion

The present paper summarizes initial results for the 22 left breast cancer patients treated in DIBH between November 19th 2020 and

Table A1
Mean ± standard deviation of setup, imaging and treatment times extracted from Aria, manually recorded by the therapists or exported from the SGRT treatment reports.

Patient	Session duration (min) Aria logs	Setup time (min)	Monitoring duration – ceiling cameras (min)	Setup duration – InBore cameras (min)	CBCT BH duration (s)	CBCT analysis duration (s)	End CBCT to beginning BH treatment (s)	Treatment duration – InBore cameras (min)	Monitoring duration – InBore cameras (min)	Number of treatment BH
1	17.4 ± 3.1	*5.8 ± 2.0*	2.5 ± 1.5	1.7 ± 1.0	32 ± 4	*75 ± 31*	139 ± 45	4.0 ± 0.4	8.6 ± 1.6	4 ± 0
2	17.2 ± 3.4	*6.3 ± 2.6*	2.2 ± 1.3	1.5 ± 0.7	30 ± 2	*77 ± 29*	122 ± 19	4.4 ± 0.5	8.3 ± 1.2	4 ± 0
3	14.6 ± 2.8	*4.4 ± 1.4*	2.0 ± 1.3	1.1 ± 0.4	27 ± 2	*51 ± 16*	101 ± 21	4.1 ± 1.3	7.3 ± 1.2	4 ± 0
4	14.0 ± 4.3	*4.3 ± 1.0*	3.1 ± 1.1	1.2 ± 0.4	30 ± 3	*69 ± 37*	117 ± 31	3.6 ± 1.5	7.2 ± 1.6	4 ± 0
5	14.8 ± 4.5	*4.1 ± 1.9*	2.6 ± 1.5	1.5 ± 0.9	30 ± 5	*63 ± 23*	130 ± 41	4.6 ± 2.1	8.6 ± 3.0	4 ± 0
6	15.0 ± 3.1	*4.9 ± 1.5*	2.2 ± 1.1	1.4 ± 0.6	31 ± 3	*66 ± 31*	118 ± 40	3.5 ± 1.2	7.4 ± 1.6	4 ± 0
7	14.9 ± 5.7	*5.8 ± 2.6*	2.7 ± 2.5	1.4 ± 0.6	29 ± 3	*58 ± 23*	98 ± 35	2.4 ± 1.1	5.9 ± 1.0	3 ± 0
8	16.1 ± 3.8	*4.6 ± 2.1*	2.8 ± 0.9	1.2 ± 0.4	32 ± 3	*76 ± 39*	118 ± 46	4.6 ± 1.6	8.4 ± 2.1	3 ± 1
9	12.7 ± 3.5	*4.3 ± 2.4*	2.6 ± 0.9	1.4 ± 0.4	29 ± 3	*52 ± 21*	106 ± 43	2.5 ± 0.8	5.9 ± 1.0	3 ± 0
10	12.9 ± 2.0	*4.2 ± 1.7*	2.2 ± 1.0	1.1 ± 0.4	28 ± 5	*60 ± 27*	125 ± 45	3.4 ± 1.0	7.0 ± 1.1	4 ± 1
11	10.7 ± 1.8	*3.1 ± 0.7*	1.9 ± 0.7	1.1 ± 0.2	27 ± 3	*47 ± 15*	108 ± 32	2.2 ± 0.5	5.5 ± 0.8	3 ± 0
12	14.5 ± 2.7	*4.8 ± 1.4*	3.4 ± 0.9	1.3 ± 0.8	29 ± 3	*60 ± 23*	113 ± 35	3.3 ± 0.6	7.0 ± 1.2	3 ± 0
13	12.6 ± 2.7	*3.9 ± 0.8*	2.6 ± 0.9	1.4 ± 0.5	29 ± 2	*60 ± 26*	108 ± 44	3.5 ± 0.9	7.1 ± 1.2	4 ± 0
14	12.7 ± 3.0	*3.7 ± 1.4*	2.4 ± 0.9	1.2 ± 0.5	28 ± 3	*72 ± 26*	117 ± 30	3.5 ± 1.3	7.0 ± 1.7	4 ± 0
15	12.2 ± 2.1	*3.4 ± 0.7*	2.1 ± 0.9	1.1 ± 0.4	29 ± 3	*67 ± 31*	113 ± 38	3.1 ± 0.8	6.4 ± 1.0	3 ± 1
16	13.6 ± 2.3	*4.3 ± 1.3*	2.7 ± 1.2	6.2 ± 1.2	29 ± 2	*81 ± 45*	121 ± 23	2.6 ± 0.5	6.2 ± 1.2	4 ± 0
17	13.9 ± 2.5	*4.5 ± 1.2*	3.6 ± 1.5	1.3 ± 0.4	29 ± 4	*65 ± 17*	119 ± 29	3.7 ± 0.8	7.5 ± 1.1	4 ± 0
18	11.8 ± 2.4	*3.4 ± 1.2*	2.9 ± 1.5	0.9 ± 0.2	29 ± 3	*73 ± 29*	123 ± 23	2.7 ± 1.1	6.0 ± 1.3	3 ± 1
19	15.9 ± 3.8	*5.6 ± 1.9*	4.4 ± 2.0	1.2 ± 0.3	29 ± 3	*90 ± 33*	122 ± 48	4.4 ± 3.0	8.1 ± 2.7	3 ± 1
20	14.4 ± 5.7	*4.7 ± 2.8*	2.8 ± 2.9	1.7 ± 2.3	27 ± 3	*71 ± 28*	114 ± 34	3.6 ± 1.4	7.6 ± 3.1	4 ± 1
21	17.6 ± 4.3	*4.2 ± 1.5*	3.8 ± 1.8	1.7 ± 1.1	28 ± 2	*82 ± 36*	143 ± 33	4.7 ± 1.3	9.2 ± 1.8	4 ± 1
22	12.4 ± 2.3	*3.5 ± 1.1*	2.9 ± 1.1	1.0 ± 0.2	27 ± 2	*66 ± 21*	117 ± 40	2.7 ± 0.5	6.2 ± 0.7	4 ± 1

March 15th 2021 on Halcyon™ with the first clinical version of AlignRT InBore™.

Fig. 1 highlights large inter and intra-patient variability for both session duration and setup times. Session duration may be overestimated being computed from the patient open/close events registered in Aria's log files which do not take into account early file load or late close events; this is confirmed by the monitoring duration of ceiling and InBore™ cameras which is on average ~30% lower. Another explanation for the large variability in session duration is patients own learning curve, improved/more precise coaching instructions and the therapists' learning curve (cf. Fig. 2). It is also worth noting that no correlation was observed between session duration (and setup time) and patients' age or body mass index ($R^2 < 0.3$).

Average CBCT shifts applied online by the radiation therapists (cf. Fig. 3) remain well below 3.5 mm in all directions (<5.5 mm in magnitude) and are in line with the local planning margins. One possible explanation for the larger vertical shifts observed in Fig. 3 may be the sub-optimal coaching window/thresholds as well as insufficient instructions and patient training. Another possible explanation is inherent to the 3 DOF Halcyon™ treatment couch limitation and the X-ray image registration algorithm. Indeed, in this case CBCT shifts may be overestimated with large translational shifts to compensate for residual rotation errors.

This study findings proved similar to literature data reporting the reproducibility of DIBH based on MV planar imaging analysis where breast/chest wall positioning was found to be within 5.0 mm of expected position for laser-based DIBH [18], within 3 mm for RPM-based DIBH [19] and within 6 mm for SGRT-based DIBH [16,17,20]. Similarly, BH stability was found to remain within 0.5 mm with visual coaching [19] and 3 mm without any visual guidance of the patient during delivery [18].

The offline review of 115 CBCT images performed by the senior oncologist leading this study proved the position of all organs to comply with local clinical and dosimetry margins (average magnitude shift well below 5 mm – cf. Table 1). It is however worth noting that shifts on the diaphragmatic domes position could not be determined for all patients as these structures fell outside the CBCT FOV. Table 1 also highlights the compromise one takes when looking at all structures in the CBCT versus individual registration of each organ. When applying such CBCT shifts, all organs except the diaphragmatic domes are likely to be within 2 mm of the expected position. In opposition, should the decision be made solely relying on the position of the diaphragmatic domes (and consequently on the lung volume and filling) may result in inaccurate positioning of the heart.

As a subsequent result of this work, several improvements to the local practice have been introduced. A dedicated patient coaching and training session is scheduled two days prior to the simulation and CT acquisitions session. In the coaching session, the patient is instructed to carry out 10 consecutive BH while filling their lung without arching their back to insure reproducible DIBH (using 6 DOF surface tracking). Only patients capable of repeating and maintaining the DIBH position in the 10 consecutive BH are thereafter considered eligible to DIBH. Day to day repeatability of DIBH and patient's ability to comply with previously established references are verified during the simulation session prior to CT acquisitions. Lastly, patients are now treated with an abdominal breathing maneuver (A-DIBH) which was found to be easier to reproduce as opposed to the previously used thoracic breathing maneuver (T-DIBH) [28].

To ensure appropriate and reproducible lung filling (T-DIBH) during A-DIBH we add a part of the abdomen in the monitoring ROI [29] and we use the deformation module (3D deviations with colors) to ensure that the patients inhale by inflating the belly as much as possible.

As a single-centre retrospective study on a limited data sample for the first 22 patients treated on Halcyon™ in DIBH with AlignRT InBore™ guidance, the present work involves several limitations. ARIA or manual timelapse recording are likely to over-estimate the treatment duration while relying only on the SGRT time recordings would not count for any time spent with the patient prior or after SGRT monitoring. Additionally, patients were instructed to breath in from their nose (and not the mouth) to achieve thoracic BH. Improved coaching instructions and a dedicated training session with appropriate surface monitoring should allow for smoother patient care. As a time-consuming task, the offline review of CBCT images was only performed on a randomly-selected single CBCT per week with a total of 115 images corresponding to 115 sessions (out of 520 sessions, i.e. 22% of the total CBCT acquisitions) were reviewed for all 22 patients.

Conclusion

Using AlignRT InBore™, left breast cancer patients treated on Halcyon™ can benefit from the DIBH technique with treatment sessions within 15 min. SGRT-guided DIBH sets the heart and internal organs within 5 mm of their expected position compliant with local clinical and dosimetry margins as proven by the offline review of CBCT images. Based on this work, several improvements were implemented including the use of a dedicated coaching session prior to CT simulation. Future work will include a comprehensive dosimetry comparison and robustness analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1.

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