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Original Article

Spirometer-guided breath-hold breast VMAT verified with portal images and surface tracking

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ABSTRACT

Background and purpose: Fast rotating closed-bore gantry linacs are ideally suited for breath-hold treatments due to reduced imaging and delivery times. We evaluated the reproducibility and stability of spirometer-guided breath-hold breast treatments, using intra-bore surface monitoring and portal imaging on Halcyon (Varian Medical Systems).

Materials and methods: Seven left-sided breast cancer patients were treated in breath-hold using the SDX spirometer (Dyn'R) with an integrated boost volumetric arc protocol on Halcyon. A dual depth-camera surface scanning system monitored the left breast. The interfraction, intrafraction and intrabreath-hold motion was determined in the anterior-posterior (AP) and superior-inferior (SI) direction. Portal images (PI), acquired at a tangential gantry angle were manually registered to the planning-CT to determine inter- and intrafraction breath-hold errors for the SI and tangential-anterior-posterior ("AP") axis. Correlations between PI and surface imaging deviations were investigated. To evaluate workflow efficiency, the total time and the number of breath-holds were recorded.

Results: Systematic and random variability of breath-hold amplitude was below 0.7 mm for the AP and below 1.2 mm for the SI component as detected by surface monitoring ($N = 130$). Systematic and random errors retrieved from portal images ($N = 140$) were below 1.2 mm for the "AP" and 2.1 mm for SI axis. A limited correlation was found between PI and surface monitoring deviations for both the SI and "AP" axes ($R^2 = 0.27/0.38$, $p < 0.01$). 75% of fractions were completed using four breath-holds and 82% within 10 min.

Conclusion: Surface imaging indicated spirometer-guided breath-hold VMAT breast radiotherapy can be accurately and quickly performed on a closed-bore gantry linac. Intra-bore surface scanning proved a valuable technique for monitoring breathing motion in closed-bore systems.

Deep inspiration breath-hold radiotherapy has become a mainstay for left-sided breast cancer patients. A decrease in mean heart dose compared to free breathing treatment has been shown [1,2] and for some patients a benefit in the mean lung dose and V_{20Gy} is observed [3,4,5]. As reproducible breath-holds are of paramount importance, the number of breath-holds per fraction should be kept to a minimum to limit patient fatigue and motion [6]. Furthermore the total time spent on the couch has been shown to correlate to the baseline drift of breast cancer patients treated in free breathing [7,8] and possibly affects breath-hold treatments as well [9]. The fast imaging and delivery capabilities of the closed-bore fast-rotating Halcyon linac (Varian Medical Systems) make it well-suited for breath-hold treatments. Cone-beam CTs (CBCTs) can be acquired within 17 seconds allowing for single breath-hold volumetric imaging to verify the setup and breath-hold performance [10]. Improved gantry rotation and leaf speed allow for a faster VMAT or IMRT delivery with similar plan quality compared to conventional C-arm linacs for a range of indications [11,12,13].

There are however limited options to verify and assist breath-holds on this system. Commercial ceiling-mounted surface scanning systems (Catalyst, C-RAD and AlignRT, VisionRT) monitor the entire chest or a limited region of interest of the patients. Due to the closed-bore configuration, patient setup is performed in front of the bore where surface scanning systems can aid in accurate positioning. However, after translation to the treatment isocenter, surface monitoring is no longer possible as there is no unhindered view of the patient. Recently, an intra bore solution has been commercially released with promising results [14], yet the system is still in a non-clinical state and applications on patients are still awaited. Also, dedicated spirometer devices are available (ABC, Elekta and SDX, Dyn'R). To the best of the authors

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knowledge, only these systems are available to be used clinically within the Halcyon bore, however with manual beam gating. Since the inhaled and exhaled lung volume measured by a spirometer device is a surrogate for the breast position, several studies have investigated the suitability of this technology for breast breath-hold tangential treatments, using either portal images to assess the heart-chest wall distance and chest wall motion during breath-holds [15] or infrared surface markers to visualize breast motion at discrete points [16], yet no evaluation on the entire breast has been performed.

In this study we investigated the breast position during spirometer-guided breath-holds in VMAT treatments combining both intra-bore surface monitoring and portal imaging on the Halcyon linac. An in-house dual depth-camera surface scanning system, developed for intra-bore motion tracking on the Halcyon linac [17], monitored the left breast during treatment. Concurrently, internal imaging was performed by acquiring portal images to evaluate the lung and breast contour.

Materials and methods

Simulation, planning and treatment workflow

Seven patients (ages 68–74) referred to the department for radiotherapy of the left breast after breast conserving surgery were prospectively included in this study, approved by the Internal Review Board, after signing of an informed consent form. All patients received a coaching session prior to the CT-simulation appointment to familiarize them with the spirometer device (SDX system, Dyn'R France). The patient-specific breath-hold level was placed at 85% of the maximal breath-hold level as per vendor recommendations. Patients were trained to maintain this breath-hold for a minimum of 25 seconds. Both a free-breathing and a breath-hold CT were acquired with both arms up on a chest board (Posirest, Civco). Target volumes and organs-at-risk were contoured according to the ESTRO guidelines [18].

A volumetric modulated arc radiotherapy plan with simultaneous integrated boost (VMAT-SIB) plan was generated for the Halcyon linac (Varian Medical Systems) on the breath-hold CT, delivering 21 fractions of 2.66 Gy to the tumor bed volume and 2.17 Gy to the entire breast. For the purpose of this study our VMAT-SIB planning protocol was adapted allowing completion of each arc in one single breath-hold for the majority of patients. Similar to Virén et al. [19], Tyran et al. [20] and Nicolini et al. [21], a two partial arcs (from ~300° to ~170° gantry angle, where the starting angle can be varied depending on the position of the contralateral breast) with orthogonal collimator rotations (~10°/280°) technique was used with the addition of a third partial arc with the same gantry angles to reduce delivery time per arc to approximately 25 seconds.

During each treatment fraction, patients were connected to the spirometer system and initial setup was performed at the Halcyon setup isocenter (approximately 60 cm in front of actual linac isocenter), using the ceiling-mounted AlignRT (VisionRT Ltd., UK) system based on the free breathing CT scan body contour surface, following our departmental protocol for breast cancer patients. The treatment couch was shifted into the linac bore and subsequently a kV-CBCT was acquired in breath-hold monitored by the spirometer signal. Online registration to the planning CT was performed using our in-house "traffic-light" IGRT protocol. After an initial automated three degrees-of-freedom (DoF) registration of the left breast, the lung contours, body contour and position of the surgical clips were assessed. All translational corrections were applied for every fraction. Gating of the treatment delivery was performed by the RTT interrupting the beam manually when the patient exited the breath-hold tolerance window (±0.1 L). In between the CBCT and VMAT arcs the patient was allowed to regain their breath before continuing.

Surface imaging, portal images and spirometer signal acquired during VMAT delivery

During treatment, an intra-bore surface scanning system monitored the patient from completion of the setup until the end of radiation delivery. The system consists of two Kinect™ for Windows cameras (Microsoft, Redmond, USA) mounted at the back of the Halcyon bore to image the patient while at the treatment isocenter. The cameras use structured-light technology to acquire depth information from which the patient's body surface is reconstructed at 4 Hz. Every fraction, a region-of-interest was delineated on the first reconstructed surface after completion of setup, which is then tracked by way of an Iterative Closest Point (ICP) 6DoF rigid registration. This system is described and the accuracy evaluated in Delombaerde et al. [17].

Concurrently, continuous portal imager frames were captured during VMAT delivery at a rate of 15 Hz using the iTools framegrabber hardware and software (version 2.2.0.1, Varian Medical Systems) attached to the EPID. An in-house software tool in MATLAB (R2017b, The Mathworks, Inc., Natick, USA) extracted the frames taken at a tangential angle (301°), either at the start or end of every arc. The exact acquisition time of this frame is available through the timestamp information in the image. The portal images were enhanced using the MATLAB-native unsharp masking method.

For every breath-hold the spirometer signal was exported from the SDX software and manually synchronized to the surface imaging signal by aligning the sinusoidal baseline breathing, as no timestamp information was available in the exported format. Due to the nature of the SDX spirometer system, the patient's breathing is only monitored shortly before a breath-hold, to establish baseline breathing, and during the breath-hold. The course of an entire fraction is shown in Fig. 1 with all available data indicated. The surface imaging provides an uninterrupted signal of patient motion and breath-hold performance, whereas internal imaging and spirometer data provide only a snapshot and/or a surrogate for the target position.

Inter and intrafraction variations and intra breath-hold stability detected with surface monitoring

The intra-bore surface scanner tracks the position of the left breast of the patient continuously in 6 DoF – anterior-posterior (AP), left–right (LAT) and superior-inferior (SI) and yaw, pitch and roll. The amplitude – AP and SI – of every breath-hold was extracted from the surface scanning signal by calculating the difference between the mean of the breath-hold level and the mean of the preceding four regular breathing cycles. The *interfraction* variations were determined by subtracting the mean breath-hold amplitude per fraction from the mean breath-hold amplitude during the first fraction, following Mittauer et al. [22]. The *intrafraction* variations were defined as the minimal breath-hold subtracted from the maximal breath-hold within each fraction, representing the worst case scenario. The effect of the number of breath-holds per fraction on the intrafraction variability was investigated by linear regression for all patients. A linear fit was performed on every breath-hold from which slope indicates the *intra-breath-hold* variability, as shown in Fig. 1.

Intra and residual interfraction errors detected with portal images

Intra and residual interfraction errors were determined by registering all portal images to the lung and body contours delineated

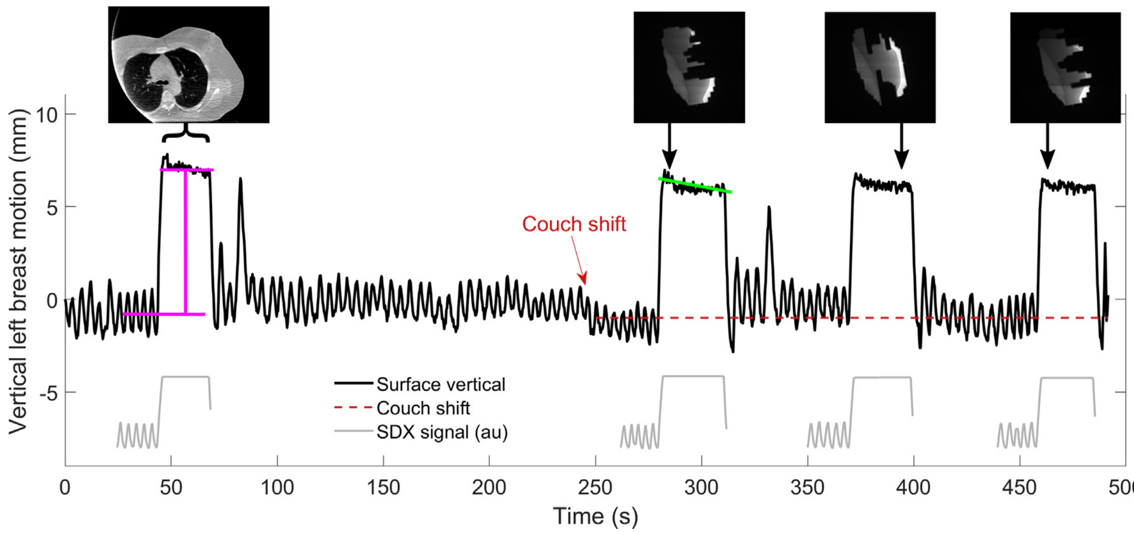

Fig. 1. All available data shown for 1 treatment fraction, from the end of setup until the retraction of the treatment couch. Surface date (only the vertical (anterior-posterior) component is shown for clarity) provides a continuous signal of patient motion, whereby baseline drift and (possible) motion after couch shifts can be detected. Internal imaging is available during the verification of the setup and breath-hold (single breath-hold CBCT) and once per arc (portal images). The spirometer signal (here shown in arbitrary units) is only acquired shortly before and during imaging or irradiation. This patient displays some intra breath-hold relaxation in the surface signal, which is not reflected in the perfectly flat spirometer signal. For every breath-hold the amplitude was extracted as the mean excursion from baseline, as shown in magenta. To determine the rate of intra breath-hold relaxation a linear fit was performed as shown in green, and the slope extracted.

on the planning CT. In the treatment planning system (Eclipse v15.6, Varian Medical Systems) a DRR was generated at 301° gantry angle with the projected body and lung contour as an overlay, shown in Fig. 2. All registrations were performed by the first author (LD), in one sitting per patient to improve consistency. The SI and tangential anterior-posterior (indicated by "AP") errors were collected. The lung-chest wall interface was used as a guide to determine the "AP" error and the body contour for the SI error. The residual interfraction setup-error was calculated based on the residual error retrieved from the portal image of the first arc of each fraction. Intrafraction set-up error was determined from the difference of the set-up error between the last arc and the first arc. Errors were quantified with their systematic (Σ) and random (σ) component for the SI and "AP" axes.

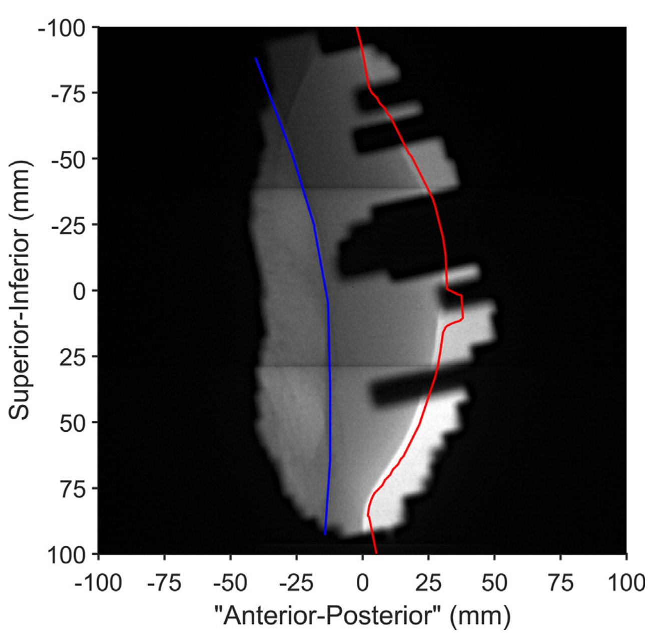

Fig. 2. Unregistered portal image at 301° with the lung contour (blue) and body contour (red) superimposed for the third arc of the first fraction for patient 3. Manual registration gave "AP" – 1.31 mm and SI -2.18 mm errors. As raw frames are acquired, without e.g. flat field or gain correction, artefacts such as the edges between detector bands are visible.

Agreement between the surface monitoring and portal images

As at the moment of portal image acquisition (indicated by arrows in Fig. 1) the surface imaging signal was also acquired, the correlation of errors detected by both methods was investigated. Both systems use a different reference – portal images are registered to the planning CT and surface imaging is a relative signal to the first frame of the fraction. The relative surface imaging signal is related to the planning CT as follows. The surface scanning signal was extracted, averaged over 2 seconds at the moment of portal image acquisition. The mean breath-hold amplitude at CBCT acquisition was subtracted from this signal. After correction for the couch shift, all deviations from zero are intrafraction errors and can be compared to their respective portal image detected error. A graphical explanation is provided in the additional materials. The SI errors from the portal images directly relate to the SI errors of the surface monitoring. The "AP" component was generated by combining the AP and lateral surface monitoring component as follows,

$$''AP''_{surface} = AP_{surface} \cdot \sin\left(301^{\circ}\right) - LAT_{surface} \cdot \cos(301^{\circ})$$

A linear regression was performed to determine the correlation between the portal images and surface imaging detected errors.

Single breath-hold imaging and delivery efficiency

The total time spent on the couch from the end of the setup until the end of radiation delivery and the number of breath-holds required were extracted from the surface image data. If a patient had to be repositioned after imaging, either due to out-of-tolerance misalignment of the target volume or because the patient was allowed to relax off the treatment couch if reaching the breath-hold level proved difficult, this additional time was included in the analysis. Three illustrative fractions are shown in Fig. 3. The presence of a learning curve for the SDX system (and

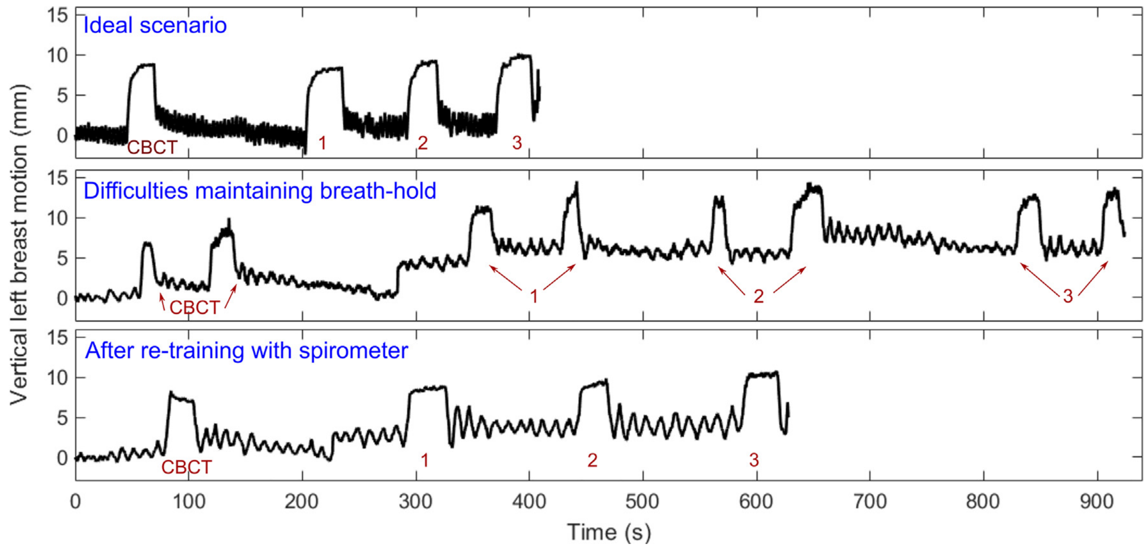

Fig. 3. The vertical (AP) left breast motion of three fractions of two different patients with the CBCT acquisition and three arcs indicated. (top) The ideal scenario in which a patient can maintain a single breath-hold during imaging and treatment delivery, resulting in a time spent on couch below 7 min. (middle) A fraction in which the patient had difficulties maintaining the breath-hold resulting both in irregular breath-holds, as well as irregular baseline breathing. This patient was re-trained with the spirometer device, resulting in longer breath-holds and a reduced fraction duration for succeeding fractions (bottom).

the treatment workflow) was assessed by linear regression of the fraction number to the fraction duration.

Results

A total of 130 out of 147 fractions had surface imaging data available for the entire fraction. Every individual patient had at least 16 complete fractions monitored. Inter and intrafraction variability of the AP and SI breath-hold amplitude is shown in Fig. 4. Systematic and random variability of the AP breath-hold amplitude was $\Sigma = 0.7$ and $\sigma = 0.8$ mm and was $\Sigma = 1.1$ and $\sigma = 1.0$ mm for the SI amplitude. For 4 (out of 7) patients a positive correlation was found between the intrafraction error and the number of breath-holds per fraction ($p < 0.01$ for all 4). For 2 (out of 7) no correlation could be determined as these patients never required 5 breath-holds or more to complete a fraction.

Most patients displayed negligible intra breath-hold variability in the AP component, 69% of all breath-holds had a change of amplitude less than 0.04 mm/s, or 1 mm for a 25 s breath-hold. Only 25% of breath-holds had a relaxation or decrease in AP amplitude, 75% an increase in amplitude, showing a possible retarded chest motion compared to maximal lung filling, as the patient at the top of Fig. 3 exhibits.

A total of 140 out of 147 fractions had portal images available for every arc. Per patient residual inter and intrafraction setup and breath-hold errors for the "AP" and SI are shown in Fig. 5. Systematic (Σ) and random (σ) errors are calculated from the registrations of the first arc, Table 1.

The weak correlation for the superior-inferior and pseudo anterior-posterior axes is shown in Fig. 6. The slope for the SI axis 0.36 (95% CI = 0.29, 0.42) and 0.48 (95% CI = 0.42, 0.54) for the "AP" axis. 73% of the "AP" errors had less than 2 mm difference between the surface imaging and portal image error whereas only 59% of SI errors agreed to within 2 mm.

The median time spent on the couch from the end of setup until the end of radiation delivery was 7 min 36 seconds (see additional

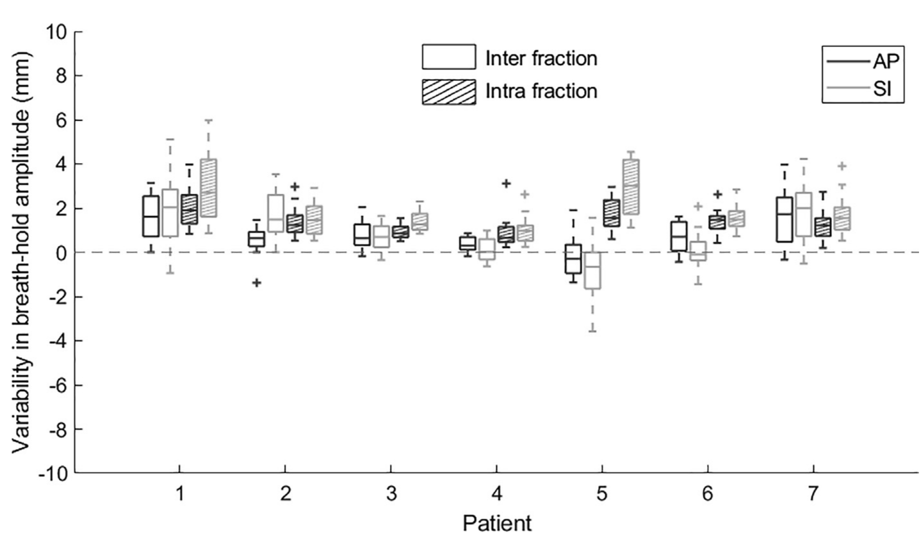

Fig. 4. Inter and intra fraction variability of the breath-hold amplitude, as detected by the surface scanning system.

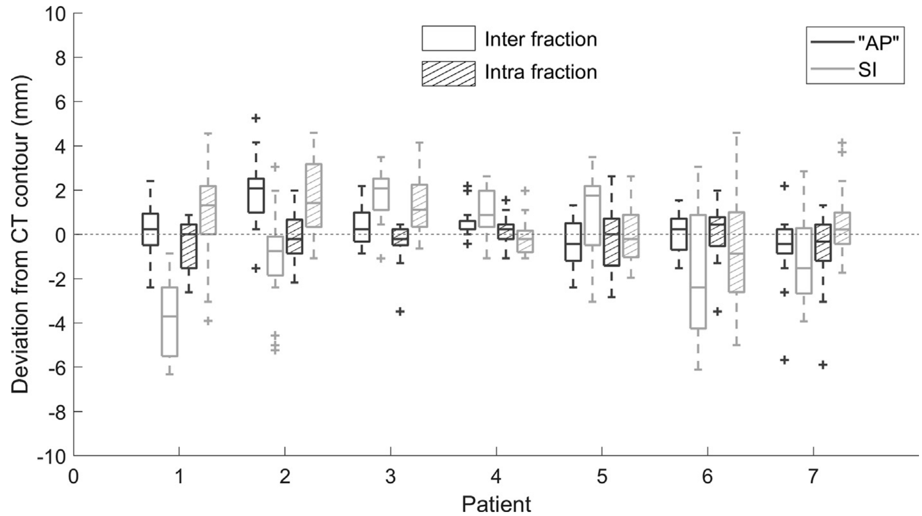

Fig. 5. Residual inter and intra fraction errors determined using portal images for every patient. A larger spread is observed compared to surface imaging detected inter and intrafraction variability.

Table 1
Systematic and random errors for the portal imaging analysis.

	"AP" (mm)	SI (mm)
	Portal Image	Portal Image
Systematic Σ	0.8	2.1
Random σ	1.2	1.9

materials for figure). Online position verification required median 1 min 37 seconds (or median 18 % of the total time). 78% of fractions were completed within four breath-holds, 14% within five breath-holds and 8% required more than five. Two (out of 130) fractions required over 30 minutes as the (same) patient had difficulties maintaining the breath-hold and had to be repositioned and re-imaged in between arcs in both cases. A small negative correlation was found between fraction number and the fraction duration for two (out of seven) patients ($p = 0.01$ and $p < 0.01$).

Discussion

Using a spirometer device, we performed breath-hold VMAT breast treatments in a closed-bore gantry linac. An in-house developed intra-bore surface scanning system monitored the patients breast motion and detected good inter and intra fraction reproducibility. Even in an older patient population of on average 70 + years of age, the majority of breath-hold treatments were completed using five breath-holds or less and within 10 minutes.

This is the first study that reports on intra-bore motion monitoring on Halcyon using surface scanning technology. As at the beginning of this study, no commercial system allowed for monitoring of the patient at the treatment isocenter, a compact system was developed as described in [17]. A distinct advantage of surface scanning technology is that continuous tracking of the patient's body can be performed as no additional radiation is delivered. Furthermore the entire breast – the target volume - can be monitored, compared to infrared markers which only display the motion of a point, previously used to assess spirometer-guided breath-hold

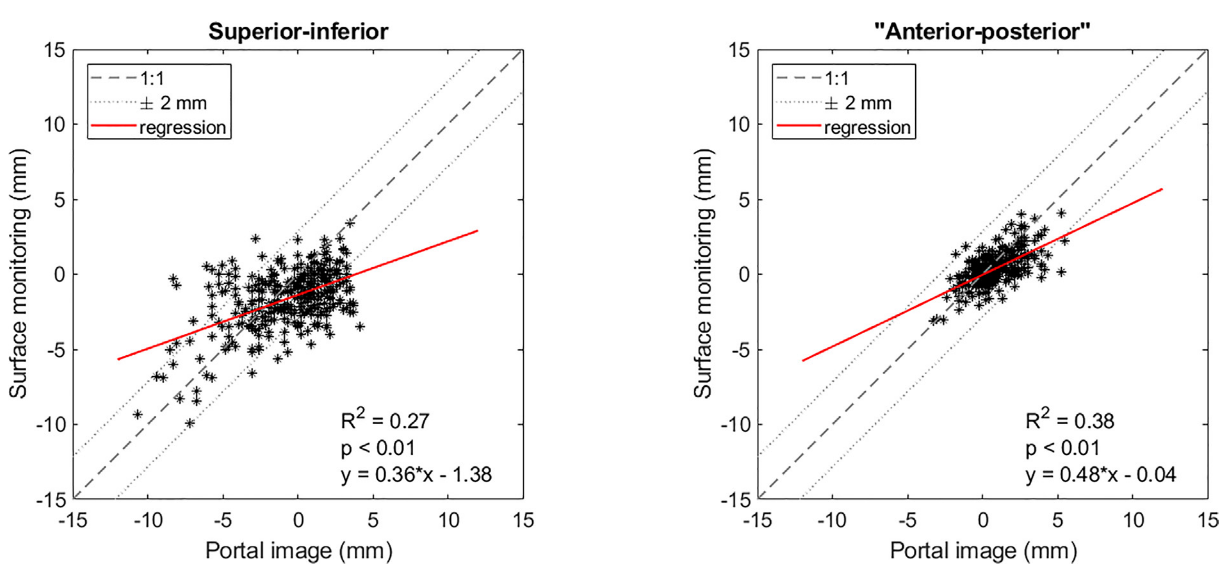

Fig. 6. Correlation between the portal image detected errors and the surface monitoring detected errors at the same time point. The dashed line denotes the theoretical one-to-one relation, the dotted line a ± 2 mm band.

treatments. Mittauer et al. [22] uses a single infrared marker placed on the xiphoid process for ABC spirometer guided breath-holds and detects intra fraction AP and SI variations of 0 to 5 mm, comparable to our results using the entire thoracic surface. Fassi et al. [16] assessed the intra breath-hold, intra and inter fraction variability of SDX spirometer guided breath-holds using a laser system focused on seven to eleven IR markers placed on the chest and abdomen. Due to the nature of the definitions only the intra breath-hold stability can be directly compared. Similar deviations are observed; between 1 and 2 mm of median intra-breath hold deviation. Surface scanning based gating shows better intra breath-hold stability, as was measured by Reitz et al. [23] using a linear fit, similar to our approach. They detect median drift of only 0.4 mm within the gating window. The left–right component and three rotations are not reported in this work as they only vary minimally in between breath holds.

Internal imaging was available once per arc by portal images. Systematic and random errors were below 2.1 mm which is consistent with previous studies assessing breath-hold reproducibility applying different methods [24,25,26,27,28]. There are however several sources of uncertainty in portal image registration. Only a partial view of the breast contour was visible due to shielding by the collimator leafs. The high weights on the ipsilateral OARs during VMAT-SIB optimization force the majority of the dose to be delivered from 'tangential' angles. This results in a large MLC aperture for these angles making both the lung contour and breast partially visible at this gantry angle, however with different apertures for every arc and every patient. Additionally, assessment of the SI setup error was hampered as the chest wall only provides minimal superior-inferior information, an effect observed by Topolnjak et al. [29]. Several authors have evaluated setup errors and breath-hold performance using portal images. Both Doebrich et al. [30] and Lutz et al. [25] assessed the intra-breath hold lung depth (the tangential AP axis in our study), but do not measure the superior-inferior variability during RPM-guided tangential breath-hold treatments.

Only a weak correlation was observed between the portal image detected errors and surface monitoring detected errors for both the SI and "AP" axes. The expected one-to-one relation is not observed as the slope of the linear fit is below 0.5 and the SI results display a high variability. Rong et al. [9] investigated the correlation between AlignRT deviations and chest wall excursions on portal images during breath-hold treatments using the RPM system (Varian). They also observe a correlation for the AP component with a slope of 0.5, however their detected excursions have a higher range (errors > 5 mm are observed) and no correlation for the SI component is given. An uncertainty is the different use of reference between the surface imaging error and the portal image error. As we use the surface imaging signal at the moment of CBCT acquisition (corrected with the couch shift) as the reference, we suppose a near perfect online CBCT registration to the planning CT. Offline verification of the online matching found differences between the breast surface on planning CT and the registered CBCT to be within 2 mm. Additionally, we suspect the inherent difficulties encountered in planar portal image registration (most pronounced in the SI axis) are a contributing factor. The portal image registration was performed by a single person to improve consistency, yet repeating the registration at a different time might have resulted in slightly different results as intra (and inter) observer variability is reported to be around 1–2 mm [31,32].

Treating left-sided breast cancer patients using a combination of fast VMAT delivery on the Halcyon linac and spirometer-guided breath-holds with the SDX spirometer, proved efficient. A large majority of fractions (84%) were completed in 10 min or less from the end of setup until the end of radiation delivery. The timing of each fraction does not take into account the time required for setup with the spirometer device and AlignRT. Adding an additional four minutes for setup, the majority of fractions (88%) could still be completed within a 15 min timeslot, therefor only requiring a minimal additional time investment for most departments. For two patients a small learning curve/adoption to the spirometer was found where the time required per fraction decreased during the treatment course. One patient required multiple treatment sessions above 30 min. because of issues with the spirometer mouth piece in part due to loose dentures. Re-training this patient in a dedicated session resolved these difficulties improving the efficiency. A larger number of breath-holds per fraction resulted in an increased intrafraction error for all patients who required more than five breath-holds supporting the trend also observed by Kapanen et al. [6] for voluntary breath-holds.

In conclusion, breath-hold breast VMAT treatments using a spirometer device are shown to have a good reproducibility as detected by continuous surface monitoring. Portal images provide internal imaging at discrete time points, however should be interpreted with caution due to limited information. Analysis of the workflow efficiency shows that DIBH treatments in the fast Halcyon system are feasible with a minimal amount of breath-holds, even in a population above 70 years of age. To limit the intrafraction error the number of required breath-holds should be kept to a minimum.

Conflicts of Interest

This work was supported by Varian Medical Systems.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radonc.2021.01.016.

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