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Original Report

Can surface imaging improve the patient setup for proton postmastectomy chest wall irradiation?

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Abstract

Purposes/Objectives: For postmastectomy radiation therapy by proton beams, the usual bony landmark based radiograph setup technique is indirect because the target volumes are generally superficial and far away from major bony structures. The surface imaging setup technique of matching chest wall surface directly to treatment planning computed tomography was evaluated and compared to the traditional radiograph-based technique.

Methods and materials: Fifteen postmastectomy radiation therapy patients were included, with the first 5 patients positioned by standard radiograph-based technique; radiopaque makers, however, were added on the patient's skin surface to improve the relevance of the setup. AlignRT was used to capture patient surface images at different time points along the process, with the calculated position corrections recorded but not applied. For the remaining 10 patients, the orthogonal x-ray imaging was replaced by the AlignRT setup procedure followed by a beamline radiograph at the treatment gantry angle only as confirmation. The position corrections recorded during all fractions for all patients (28-31 each) were analyzed to evaluate the setup accuracy. The time spent on patient setup and treatment delivery was also analyzed.

Results: The average position discrepancy over the treatment course relative to the planning computed tomography was significantly larger in the radiograph only group, particularly in translations (3.2 ± 2.0 mm in vertical, 3.1 ± 3.0 mm in longitudinal, 2.6 ± 2.5 mm in lateral), than AlignRT assisted group (1.3 ± 1.3 mm in vertical, 0.8 ± 1.2 mm in longitudinal, 1.5 ± 1.4 mm in lateral). The latter was well within the robustness limits (±3 mm) of the pencil beam scanning treatment established in our previous studies. The setup time decreased from an average of 11 minutes using orthogonal x-rays to an average of 6 minutes using AlignRT surface imaging.

Conclusions: The use of surface imaging allows postmastectomy chest wall patients to be positioned more accurately and substantially more efficiently than radiograph only–based techniques.

Introduction

The conventional treatment techniques for postmastectomy radiation therapy treatment (PMRT) use a combination of photon and electron beams involving multiple matching fields.

Conflicts of interest: None.

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The resulting dose distribution is often a compromise between robust target coverage, for internal mammary nodes in particular, and heart/lung sparing. Different techniques have been explored to reduce the dose to cardiac tissues, including deep inspiration breath-holding and, recently, the use of proton beams with significant advantages in sparing organs at risk without compromising target coverage.[1,2]

Pencil beam scanning (PBS) PMRT is now routinely offered at Massachusetts General Hospital (MGH). Using a single field and intensity modulation, PBS-PMRT improves the treatment for patients with or without implant by achieving complete target coverage of chest wall and all involved nodal regions while substantially reducing dose to cardiac/lung structures.[3] The treatment was shown to be adequately robust against both setup uncertainties (±3 mm along each translation axis, and ± 2° around each rotation axis) and patient breathing motion from quiet respiration.

Traditionally, patient setup for proton beam treatments relied on radiographs. At our institution, the patient is first positioned using tattoos and lasers. A set of orthogonal radiographs is taken at a cardinal gantry angle to verify the patient's body posture and to place the patient precisely at the isocenter. A beamline radiograph is then performed at the treatment gantry angle to finalize the set-up position. Although the technique works well for most of the treatment sites, it is not the most appropriate for superficial target volumes away from the major bony anatomical structures, such as PMRT cases.

Surface imaging has been used in clinical practice for at least 20 years[4] and was successfully implemented at MGH in the photon clinic for partial breast irradiation, deep inspiration breath-holding breast treatment, and the treatment of extremity sarcoma.[5,6] The technique can capture patient body surfaces in 3 dimensions with millimeter accuracy and use the data to guide patient positioning during setup. This is particularly valuable and relevant for treatment of superficial target volumes because the positioning process relies on matching of these target volumes themselves, rather than the distant bony anatomical structures. In this work, we investigate the possibility, practicality, and potential benefits of using surface imaging for patient setup in PBS-PMRT. Specifically, we want to answer the question if surface imaging can replace radiograph setup techniques for PMRT with accurate patient positioning, less imaging dose to patients, and shorter setup times.

Methods and materials

System configuration, calibration, and phantom verification

We used the AlignRT system developed by Vision RT Ltd (London, UK) with Link model stereo cameras and software version 5.0. The system hardware consists of 3 imaging pods attached to the ceiling, with each pod containing 2 cameras. The system can acquire a 3-dimensional surface model of the patient during setup and compare it with a reference surface (either generated from planning computed tomography (CT) data or captured at the time of treatment) in a user-defined region of interest (ROI). It then calculates the rigid-body transformation that minimizes the distance between the 2 surfaces and provides the couch correction (or deltas) along the 6° of freedom: 3 translations (vertical [VRT], longitudinal [LNG], and lateral [LAT]) and 3 rotations (along the vertical axis, the longitudinal axis, and lateral axis). To minimize the setup errors that could result from respiratory motion, the system is capable of gating surface captures at a specific respiratory phase. Real-time imaging of the patient is also available. The positions of the AlignRT cameras are dictated by our gantry room configuration, particularly the lower ceiling and large rotating structure compared to a regular linear accelerator (LINAC) room. The 2 side cameras (left and right) had to be moved inferiorly from the isocenter instead of the lateral positions in a typical LINAC installation, as indicated in Fig 1A. This results in suboptimal images for chest wall patients in a treatment position because of the narrow angle for the line of sight for the cameras and the long distance. In many acquired surfaces, there are unprocessed regions where the system is unable to acquire data, particularly when the view of one camera is blocked by the bulky beam nozzle (ie, at the gantry angle of the treatment). We therefore raised the breast board to the highest angle available to fully use the central camera view and limit missing data on the upper part of the patient chest. Given the flexibility of the PBS technique, the high elevations of the patient's upper body do not present any dosimetric challenges.

The standard calibration procedure for AlignRT is designed originally for LINAC treatment rooms. It uses a large thin plate with a specially designed pattern, and the plate needs to be positioned by using the stationary room lasers aligned to the isocenter of the LINAC. In the proton treatment room, most of the lasers are not stationary, but mounted on the rotating gantry. Moreover, because of the weight and size of the gantry and beam nozzle, the isocenter of the beam is not stationary either and actually shifts up to 2 mm as the gantry rotates. The AlignRT system, however, allows only 1 coordinate calibration. Given that the system is primarily for PMRT treatments that use only 2 gantry angles (±30° from vertical), we chose to calibrate the system to the average position between the 2 isocenters for these 2 gantry angles. Radiopaque markers are taped on the calibration plate; beamline and 90° orthogonal radiographs were acquired and analyzed to find the average isocenter position. Once the plate is precisely at the calibration position, the gantry is rotated to 180° to avoid camera obstruction by the beam nozzle during the calibration process. (Note that the

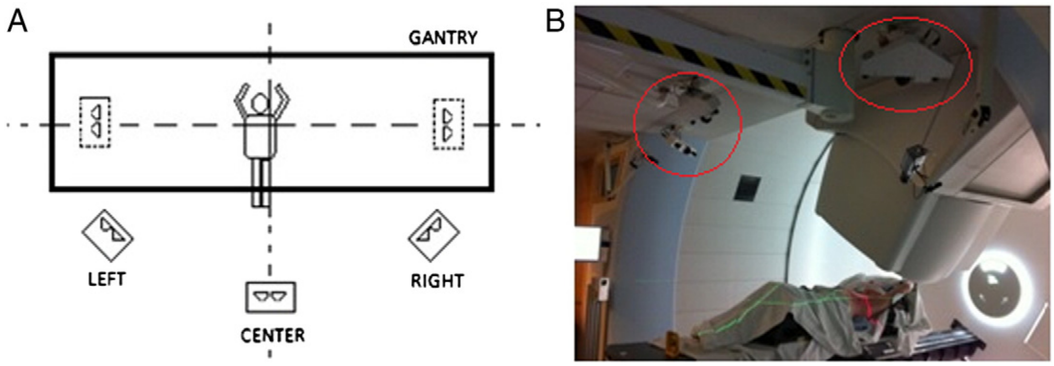

Figure 1 **(A)** AlignRT camera positions in the proton gantry room. The thicker line box marks the location of the rotating gantry structure. As a result, the 2 side cameras must be moved to outside of the gantry rotation area, instead of the location indicated by the dashed line boxes, as in a typical LINAC room installation. **(B)** Actual system in place at Massachusetts General Hospital.

average isocenter position is not necessarily the isocenter position for gantry at vertical position because of the possible mechanical hysteresis of the gantry/nozzle structure.)

The accuracy of the AlignRT system for both static and gated acquisition modes were reported in phantom as well as healthy volunteers.[7,8] A cubic phantom with 5 radiopaque markers (1 at each corner and 1 at the center of the cube) was, however, used to verify the coordinate calibration and the accuracy of the system. The phantom was fixed on the couch and positioned at the average isocenter position using x-ray imaging from the 2 gantry angles mentioned previously. An AlignRT reference image of the cube was then acquired. The couch was subsequently moved by 1 cm along each translation direction (LAT, LNG, and VRT) and by 3° around each rotational axis (vertical, longitudinal, lateral), independently. Combined rotations with 2° about each individual axis were also applied. The position correction vectors provided by AlignRT agreed with the actual couch motion. The maximum differences between AlignRT computations and expected values were 0.4 mm in translation, 0.13° in single rotations, and 0.11° for the combined ones.

During the translation/rotation tests, 2 AlignRT images were recorded for each position, and the average deltas were computed. The standard deviation computed between deltas from 2 consecutives AlignRT images were less than 0.2 mm and 0.07°.

An end-to-end test was conducted using an upper body shell mannequin, starting from CT scan to positioning at the treatment unit by AlignRT. Three radiopaque markers were used to mark the chest wall target area so that radiograph setup procedure validated the phantom position (less than 1 mm and 1°).

Application to patient positioning

AlignRT requires a reference surface image to which all captured patient surface images are compared. For this reference, one can use an image captured by AlignRT, for example, on the first day of treatment, or use the body surface generated from the patient's simulation CT data. We chose the latter to focus more on the consistency between simulation (ie, planning) and treatment. The MGH PBS-PMRT treatment time (approximately 2 minutes beam on) does not allow breath-hold treatment; a "free-breathing" helical CT scan is therefore used for planning. The CT skin and target structures as well as the field isocenter position are imported from the planning system through Digital Imaging and Communication in Medicine–Radiation Therapy. The system allows the user to define ROIs on the reference surface to limit the calculations of position correction to relevant areas. A single ROI is used, based primarily on the target area (chest wall and nodes); the ROI does not include the axilla/armpit or the upper part of the neck.

AlignRT's gating mode was used throughout the setup process to minimize the random fluctuations resulting from respiration, despite the fact that the amplitude of the chest wall motion during quiet respiration is generally small (<3 mm). In this mode, the patient respiration is monitored by a tracking point located near the middle of the abdomen and a clear respiratory signal curve can be obtained. The body surface capture then takes place only at the specified phases of the respiration cycle. We chose the end of expiration given that it is generally the most stable and reproducible phase during the breathing cycle.

Radiopaque markers were placed at 3 points during CT simulation: 2 at the level of the breast (midline and lateral side) and 1 in the supraclavicular area. The location of the markers was subsequently tattooed together with the 3 regular leveling tattoos inferiorly. During patient setup at the time of treatment, radiopaque markers are placed on the tattoos to compare position between captured radiographs and generated digital reconstructed radiographs to calculate correction vectors. These correction vectors were compared with those generated based on the traditional bony anatomy registration.

Our investigation was conducted in 2 phases and included 15 patients in total. Thirteen of them had implants with near-zero mobility, as required by the PBS-PMRT protocol. This protocol was established specifically for patients with implants because they usually present the most challenging cardiac anatomy for conventional treatment techniques by photon/electron beams.

During the first phase (first 5 patients), the patient was set up following the standard radiograph-based procedure. Surface images were captured at different time points along the process with the position corrections (or deltas) calculated but not applied. The workflow was as follows: the patients were first aligned on the breast board using in-room lasers and the leveling tattoos with the gantry at 0° and moved to the isocenter position using the shifts calculated by the planning system: radiopaque markers were placed on the 3 previously mentioned tattoos. Orthogonal radiographs were acquired and position corrections computed based on both the anatomy and the markers; if the corrections calculated based on the usual anatomical marks differ from those based on the 3 surface points, the latter was chosen for patient position correction. Additional cycles of imaging were required if the position corrections were greater than 2 mm in any translation and 1° in any rotation. The gantry was then rotated to the treatment angle (30° or 330°); a beamline radiograph was acquired and position corrections calculated and applied only based on the markers. Finally, the markers were removed and the PBS treatment field delivered.

During this radiograph setup process, the AlignRT system was activated in the gating mode to acquire surface images in the selected respiration phase. Surface images were taken at 5 time points: before and after the orthogonal radiograph step, before the beam line radiograph, and before and after the beam delivery. The system compared the captured images with the reference CT image and computed the position correction delta. These deltas were collected but not used to position patients.

The second phase of our study included 10 patients and the workflow differed from the first phase by replacing the orthogonal x-ray imaging step with AlignRT. This included taking the surface images of the patient and applying the calculated position corrections to our 6°-of-freedom patient positioner (translations and rotations). Multiple iterations may have been needed until the position corrections fell under 2 mm and 1°. A final surface image was taken to document the residual setup error compared with CT.

The beamline radiograph was performed at the end as a final confirmation of the setup. If the calculated position corrections based on surface points markers were greater than 3 mm in translation, the patient position was adjusted accordingly but by one-half of the amplitude. This is in consideration of the robustness criteria of the treatment plan.[3] As in the first phase, surface images were taken both before and after the pencil beam delivery.

Data collection and analysis

All the position corrections (or deltas) calculated by AlignRT following each surface capture were recorded for each patient's treatment fraction (28-31 fractions per patient), regardless of how they were actually applied to move the patient. Each AlignRT image capture carries a time stamp in resolution of seconds. These time stamps were used to estimate the lengths of time in each step of the process as well as the total treatment time.

Analyses were performed to evaluate the effectiveness of the skin surface markers, comparison of setup accuracies in reference to treatment planning CT data for the 2 phases (ie, with and without the use of AlignRT), and the stability of patient during irradiation.

For both phases (positioning with radiographs or positioning with AlignRT), the AlignRT images acquired just before treatment and their comparisons to CT were analyzed. The resulting systematic (S_p) and random (σ_p) residual setup errors were computed for each patient, as were the group systematic and random residual setup errors over all patients as defined by Bijhold et al.[9] and de Boer et al.[10] The S_p corresponds to the average shift over all fractions per patient and σ_p to its corresponding standard deviation. Systematic and random group residual setup errors were also computed by averaging the absolute Sp and σ_p over all patients.

The difference between the deltas provided by the orthogonal radiograph positioning system based on bony anatomy and the ones based on surface point markers, at gantry 0°, were also analyzed for the five radiographs setup patients.

Results

Immobilization improvement

After using AlignRT as an observation tool for patients traditionally positioned using lasers and radiograph imaging, the patient immobilization was modified as follows: as mentioned previously, the breast board is raised at the highest angle available to avoid missing data on the upper part of the patient's chest. Because AlignRT images provide a full view of the upper patient body instead of the restricted view of the patient's chest in the radiographs resulting from panel size limitations, it was noticed that the patient's chin and arm positions had large daily variations. A chin strap (chin at the standard spirit angle), rigid head cup and hand grips were subsequently added on the breast board. Arm and chin positions are therefore checked during each fraction and interactively adjusted by therapists using the full chest view AlignRT images. Comparison of beam line radiographs to digitally reconstructed radiographs confirmed that the position of the clavicle was within the tolerance limits of 3 mm and 2°.

Based on the AlignRT time stamps, the average time elapsed between the final setup confirmation by the beamline radiograph and the time when the patient can get up was 5 minutes. This included the actual irradiation time (approximately 2 minutes), snout extension and retraction, staff exiting and entering the treatment room, and occasional waiting because of beam availability. The patient position changes over this time period was less than 1.5 mm for translations and less than 0.6° for rotations.

Bony anatomy versus skin surface markers

The S_p and σ_p residual set-up errors between the 2 deltas for each patient of phase 1 over the course of treatment are reported in Fig 2. The resulting systematic translations group residual setup errors was 2.9 ± 1.5 mm in LAT, 1.4 ± 1.4 mm in LNG, and 2.2 ± 1.4 mm in VRT. The random group errors were superior to 2 mm with 2.1 mm in LAT, 2.7 mm in LNG, and 2.4 mm in VRT, respectively.

Patient setup accuracy compared with CT

Figure 3 shows the translational differences over the course of treatment between the planning free-breathing CT skin surface and the gated AlignRT surface images taken immediately before treatment for patients positioned by x-rays only (left) and those by AlignRT (right). The systematic and random residual setup group errors are reported in Table 1. Similarly, the values for AlignRT assisted setup are noticeably lower than those with radiograph only and well within MGH setup robustness for translations (±3 mm) and rotations (±2°).[3]

Setup and treatment time

Figure 4 shows the time elapsed for setup and treatment delivery for all the 15 patients under study. The radiograph-only procedure took 11 minutes on average (#1-5), whereas the AlignRT assisted process took only 6 minutes (#6-15). The treatment delivery time was comparable between the 2 groups, averaging 5 minutes with 2 minutes of beam on time.

Discussion

The traditional radiograph-based setup technique is indirect for PBS-PMRT treatment because of the superficial target volumes that are not visible on radiographs and far away from the major bony landmarks, potentially resulting in inadequate patient positioning.[11] The use of AlignRT allows setting up the patient directly using the surface area of the target volume with substantially improved accuracy (Fig 3, Table 1), as previously reported for photon breast irradiation.[5,12] In addition, surface imaging also offered monitoring of patient chin and arm positions, 45% shorter setup time, and elimination of imaging dose to patient from the traditional orthogonal radiograph setup technique. We have adopted this technique for all PBS-PMRT treatment at our clinic.

The introduction of the 3 radiopaque markers on skin surface clearly challenged the traditional bony anatomy only technique (Fig 2) and should, in principle, make the x-ray imaging method more relevant to PMRT treatment setup. However, the markers alone did not solve all the problems, given that all patients used these markers; however, only those (#6-15) helped by surface imaging had more accurate setup according to Fig 3. This may be attributed to several factors. For one, the markers determine the positions of only 3 points on the skin surface, whereas AlignRT used a region of interest that covers nearly the entire chest wall for surface matching. The consistency of the marker positions are also limited by uncertainties at many steps including tattooing and marker placement, but also by identification of the marker positions resulting from finite CT slice spacing and artifacts. For these reasons, we apply only one-half magnitude of the marker-based position corrections when they are higher the robustness tolerance thresholds.

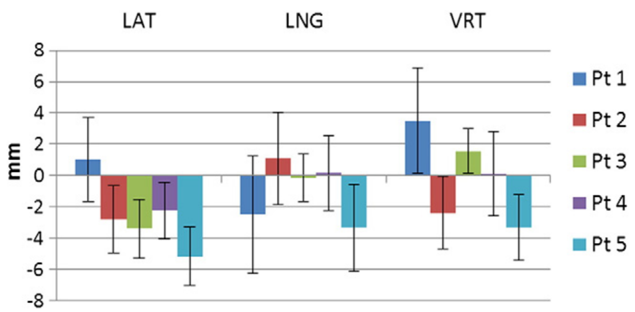

Figure 2 Systematic (S_p, histograms) and random (σ_p, errors bars) residual setup errors differences between translation deltas based on bony anatomy markers and those based on skin markers from orthogonal radiographs for the 5 patients in phase 1.

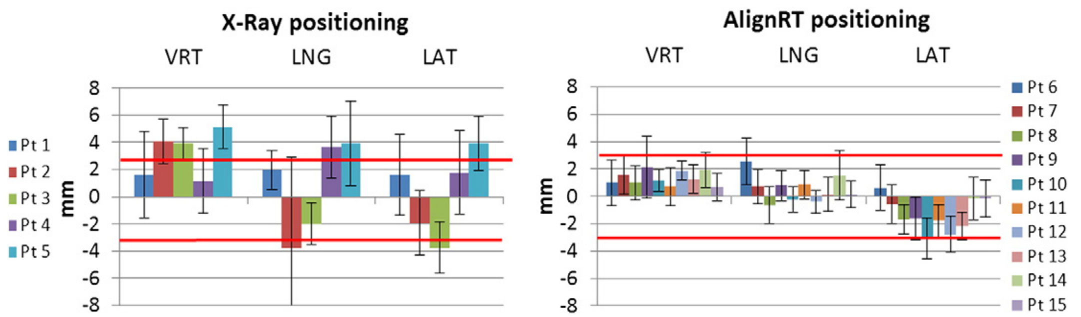

Figure 3 Systematic translations residual setup errors (S_p, histograms) and random residual setup errors (σ_p, errors bars) for chest wall patients given by AlignRT data compared with planning computed tomography, after positioning by radiograph (phase 1, patients 1-5) versus surface imaging, AlignRT (phase 2, patients 6-15). The ±3 mm Massachusetts General Hospital setup robustness for translations is represented by a red line.

Note that, even with these uncertainties, the skin markers are still valuable surrogates for setup confirmation in terms of quality control. In 1 case, exceptionally large magnitudes of position corrections were generated by the beam line radiograph after the AlignRT setup. It prompted a careful examination of the patient, only to find that the patient's implant had actually shifted, warranting replanning.

Setup with surface imaging implicitly assumes a strong correlation between the skin surface and the location of the target volume. The latter can be verified by the use of CBCT, which unfortunately is not available in our institution at this time. However, the real-time feedback of the whole patient position without the use of radiation and the use of a large ROI close to the target volume shows a clear improvement compared with radiographs.

Bert et al as well as Padilla et al reported offset in chest position resulting arm mispositioning.[13,14] An incorrect chin position may also affect the average shift computed over the whole ROI by the AlignRT software. Therefore, and as recommended by the manufacturer, the AlignRT ROI used in this study includes neither the armpit nor the upper node neck target volume. Nevertheless, arm and chin positions were improved by the addition of the hand grips and chin strap and through interactive adjustments by therapists after the patient's breast was correctly positioned, using the visual registration of the full view AlignRT images.

Our patients had free-breathing CT scans for treatment planning, with 30 seconds' average time acquisition. Because of the interplay between scanning and breathing, the resulting skin surface from the CT (ie, the reference surface used in this study) is neither an average over the breathing cycle nor an instantaneous skin surface at any particular breathing phase, and therefore would differ from any AlignRT image. Ideally, the surface of the reference setup is acquired during the treatment planning CT using a second AlignRT camera installed in the CT room. However, surface imaging cameras were not available in our CT room.

In addition, the initial version of AlignRT, with older cameras, showed small but nonnegligible fluctuations even between 2 successive static acquisitions of a phantom as reported in our system verification. To avoid adding the effect of respiration to these random fluctuations, the AlignRT surface image capture was gated to the expiration phase of the breathing cycle. This apparent breathing

Table 1 Positioning residual setup group errors in millimeters over all patients using the absolute S_p per patients represented in Fig 3

(mm)	Group 1: X rays			Group 2: AlignRT		
	Systematic errors (mean SD)		Random errors (mean)	Systematic errors (mean SD)		Random errors (mean)
VRT	3.2	1.7	2.0	1.3	0.5	1.3
LNG	3.1	1.0	3.0	0.8	0.7	1.2
LAT	2.6	1.1	2.5	1.5	1.1	1.4
Yaw	0.5	0.3	1.2	0.5	0.4	0.9
Roll	0.9	0.8	1.5	0.6	0.4	0.6
Pitch	0.5	0.3	1.0	0.4	0.4	0.6

LAT, lateral; LNG, longitudinal; SD, standard deviation; VRT, vertical

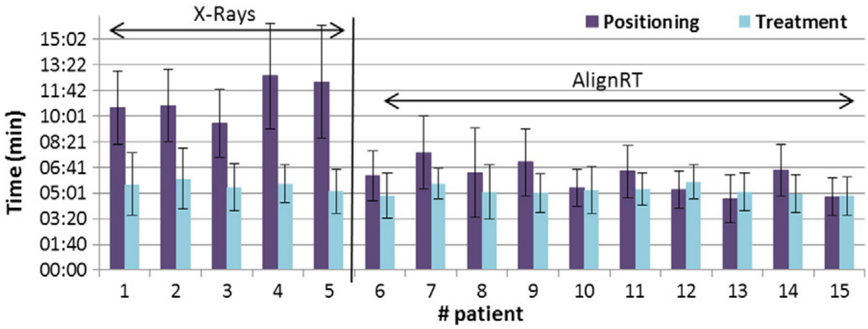

Figure 4 Treatment delivery time (light color) and positioning time (dark color) for positioning with radiographs (patients 1-5) or AlignRT (patients 6-15).

inconsistency from free-breathing CT should not be of concern, given that our previous robustness study suggested that breathing-induced uncertainties were drastically smaller than those from setup uncertainties.[3] Additionally, our AlignRT system has been upgraded recently with high frame rate and high-resolution cameras resulting in a much more stable real-time surface monitoring mode. The latter is currently under further evaluation for improving PBS-PMRT setup.

Unfortunately, our current treatment process requires the snout to be as close as possible to the patient skin surface, which results in blocking the camera views. To optimize the AlignRT image quality, all images were acquired with the snout "retracted" and the snout was moved closer to the patient just before treatment, not allowing real-time imaging during treatment.

Given the limitations in our treatment delivery system, breath-hold treatment cannot be implemented at this time.

Conclusion

Using a surface imaging system, we have found that setting up the patient directly to the surface area of the target volume can be done efficiently and accurately for PBS-PMRT. The traditional orthogonal radiograph setup procedure can be replaced entirely by surface imaging with more accurate positioning, shorter setup time, and the reduction of imaging dose to patient.

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