Machine learning-based treatment couch parameter prediction in support of surface guided radiation therapy

Geert De Kerf [a,*], Michaël Claessens [a,b], Isabelle Mollaert [a], Wim Vingerhoed [a], Dirk Verellen [a,b]

[a] Iridium Netwerk, Antwerp, Belgium
[b] Department of Radiation Oncology, Faculty of Medicine and Health Sciences, University of Antwerp, Antwerp, Belgium

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ABSTRACT

Purpose: A fully independent, machine learning-based automatic treatment couch parameters prediction was developed to support surface guided radiation therapy (SGRT)-based patient positioning protocols. Additionally, this approach also acts as a quality assurance tool for patient positioning.
Materials/Methods: Setup data of 183 patients, divided into four different groups based on used setup devices, was used to calculate the difference between the predicted and the acquired treatment couch value.
Results: Couch parameters can be predicted with high precision ($\mu = 0.90$, $\sigma = 0.92$). A significant difference (p < 0.01) between the variances of Lung and Brain patients was found. Outliers were not related to the prediction accuracy, but are due to inconsistencies during initial patient setup.
Conclusion: Couch parameters can be predicted with high accuracy and can be used as starting point for SGRT-based patient positioning. In case of large deviations (>1.5 cm), patient setup has to be verified to optimally use the surface scanning system.

Introduction

In a conventional radiation therapy (RT) workflow, reference tattooed skin markers are applied during computed tomography (CT) simulation, which are subsequently identified in the treatment planning process. If another location is defined as a more appropriate isocenter during the planning process, shifts in each of the three directions (X,Y,Z) are calculated. At the first fraction, radiation technologists (RTTs) install the patient on the treatment couch by aligning the skin markers to in-room lasers. Subsequently, the patient can be relocated according to the planned shifts. As additional support, mega-voltage (MV) portal imaging and/or radiographic 2D kilo-voltage (kV) setup projections are performed for position verification and possible adjustments and further examination of patient positioning and target may be assessed by cone-beam CT (CBCT). After approval of the image registration, the acquired couch coordinates are captured and can serve as a basis to ensure constancy in positioning during subsequent fractions of the treatment.

Despite the described number of precautions taken to accurately position the patient in a reproducible way, it remains a major challenge in modern RT. Analysis of incidents reported to the Radiation Oncology Incident Learning System (RO-ILS) showed that 18 % of the high priority

events could be attributed to either wrong shift instructions or a wrong shift performed during the treatment[1]. These prominent errors trigger the need for automating the patient setup process and optimize the patient's workflow, and mitigate the pressure on the RTTs.

Recently, Surface Guided Radiation Therapy (SGRT) has paved the way towards a complete replacement of patient's tattooing with a markerless patient's workflow and a reduction in time for patient setup in comparison to laser alignment[2]–[4]. Such SGRT systems compare and register a live patient's surface to a reference surface in order to quantify spatial positioning deviations. For initial patient setup, accuracies of<7 mm can be obtained when comparing against imaging verification for a variety of anatomical regions (breast, abdomen, chest, …)[5,6]. However, the accuracy depends on patient motion, surface shadowing, selected region of interest, anatomical changes during treatment and absence of anatomical gradients (e.g. very flat surfaces) [3,7,8]. If the region of interest of the live patient surface contains translational or rotational symmetries (limbs, flat abdominal area,…), or uniform surfaces with minimal topographic information, small deviations in spatial positioning are no guarantee for correct patient alignment. To improve accuracy, one could return to applying tattoos or fiducial markers to introduce additional information during patient

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position. As the latter is exactly what we want to avoid, advanced algorithms or predicted couch parameters seems a more efficient solution. [4,9,10]. Of course, image guided radiation therapy (IGRT) will always be required in combination with the SGRT process to ensure proper alignment of internal anatomy and target location, especially for stereotactic body radiation therapy/stereotactic radiosurgery (SBRT/SRS) cases where 6 degree-of-freedom (DoF) matches are performed. Nevertheless, couch parameter prediction allows optimizing the initial SGRT-based patient setup.

Besides the added value of automated couch coordinates prediction in an SGRT workflow, this tool can also improve quality assurance (QA) in external beam radiotherapy by preventing wrong-site treatments or wrong table shifts[11,12]. The feasibility and accuracy of estimating patient-specific couch positions has already been demonstrated in previous studies. Some studies completely depend on the embedded radio-opaque landmarks on immobilization devices, which limits the clinical use of such method in cases where no markers exist[12]. Other approaches calculate the position of the couch based on respectively couch embedded ball bearing (BBs) or couch notches[11,13]. However, both methods involve manual selection of a point on CT images during treatment planning, which is potentially subjected to user errors. Recently, an automated solution is developed to determine the treatment couch position by computerized detection of the embedded BBs and index levels on the couch from CT images[14]. Despite the automatic character, the fixed threshold to detect markers is a potential pitfall due to reduced CT contrast resulting from the partial volume effect in a voxel.

In this study, we propose a fully independent, machine-learning based approach to automatically predict treatment couch parameters in support of SGRT-based patient positioning protocols. Only stereotactic body radiation therapy/stereotactic radiosurgery (SBRT/SRS) data is used, but the approach applies to all kind of radiation therapy treatments. Additionally, the approach acts as a QA tool for patient positioning.

Material and methods

Patient selection and clinical workflow

For verification, 183 clinically, approved SBRT treatment plans were retrospectively selected. These patients were treated between December 29th, 2020 and February 10th, 2022 and covers three different anatomical regions (51 Brain, 89 Lung, 43 Prostate). All patients were simulated on a Brilliance Big Bore (Philips, The Netherlands) or a SOMATOM Go-Sim CT scanner (Siemens, Germany). During CT simulation, patients were positioned according to four different protocols. Main support devices are the Encompass SRS Immobilization System (Qfix, USA) for stereotactic brain lesions, SBRT long base plate (Orfit, Belgium) or ThoraxSupport (Macromedics, The Netherlands) for lung lesions and indexed cushions for prostate treatments (details can be found in Table 1). Treatment plans were created in RayStation 9A (RaySearch Laboratories, Sweden) and exported to Aria 16.0 (Varian, USA) for treatment delivery. At the first fraction, patients are positioned

using an SGRT system (AlignRT, VisionRT, United Kingdom) before acquiring a CBCT for final patient position verification and treating the patient on a Varian TrueBeam STX with 6 DoF couch. Patient positioning consists of multiple steps (Fig. 1). Once the patient is installed on the treatment couch, treatment couch will move to the predicted couch values to initiate the surface-guided patient setup. Secondly, RTTs use the SGRT information to manually reduce the pitch and roll error followed by automatic correction of the residual translations reported by SGRT system. At this moment, the patient's surface is positioned as close as possible to the reference surface of the TPS. Next, imaging is performed and 6D couch correction will be applied to correct for positioning errors seen on cone-beam CT (CBCT).

Automated table coordinates calculation method

To index the CT scanner's couch top, barium markers are placed underneath both department's CT scanners (Philips Brilliance Big Bore and Siemens Somatom CT). Every indexed position (H4 to H1, 0, F1 and F2), which is used for fixating support devices, is labelled by two markers, laterally separated by a unique distance Δx [cm] between 1 and 7 cm (Fig. 2). Indexing the CT couch top itself makes the couch parameter prediction support device independent as long as the couch top is part of the CT image. As the Encompass SRS Immobilization System (Qfix, USA) floats beyond the CT couch top, the radio-opaque Encompass markers, embedded in this support device, needs to be detected instead of the couch markers underneath the CT couch.

According to the International Electrotechnical Commission standard the treatment couch of our Varian TrueBeam STX is calibrated in lateral (X), vertical (Y) and longitudinal (Z) to be at position (0, 0, 140) at isocenter respectively, referred to as (TX_0, TY_0, TZ_0) according to Varian IEC. Treatment couch parameters (TX, TY, TZ) can be calculated as followed:

$$TX = X0 + Xiso + TX0$$

$$TY = Y0 + Yiso + TY0$$

$$TZ = Z0 + Ziso + TZ0$$

with $(X_{iso}, Y_{iso}, Z_{iso})$ the coordinates of the planning treatment isocenter and (X_0, Y_0, Z_0) the coordinates of the central detected marker $(X_0 = 0)$.

To detect markers on the CT image, a cropped CT will be created based on a rough estimate of the expected marker position in X and Y direction. Subsequently, a pre-processing step will be applied on the cropped CT by thresholding the image based on the higher density of the markers. The threshold value is individually defined for every CT scan as the third highest bin edge of a histogram with bins = 10. Afterwards, a K-means clustering (k_clusters = 2) algorithm will try to detect the couch markers or the cranial Encompass marker (k_clusters = 1). Finally, a post processing step will check the validity of the detected set of markers based on size of the detected clusters, Hounsfield Unit (HU) of the surrounding area and position of the detected point(s).

Once the set is validated, a mapping table between CT and linac coordinate systems, allows the algorithm to calculate the expected treatment couch position based on the difference between the marker coordinate and the isocenter of a treatment plan (Fig. 2).

Data collection and analysis

Three different table coordinates (lateral $\times$, vertical y and longitudinal z) are reported, namely predicted ($P_{x,y,z}$), setup ($S_{x,y,z}$) and treatment ($T_{x,y,z}$) couch values. The predicted couch parameters are automatically detected via the ML methodology, implemented using the integrated scripting possibilities of RayStation. In 51 cases, the Encompass SRS marker needed to be detected. Couch markers were detected in 132 cases. For analysis of the data, the setup and treatment

Table 1
Used immoblization material for different positioning protocols.

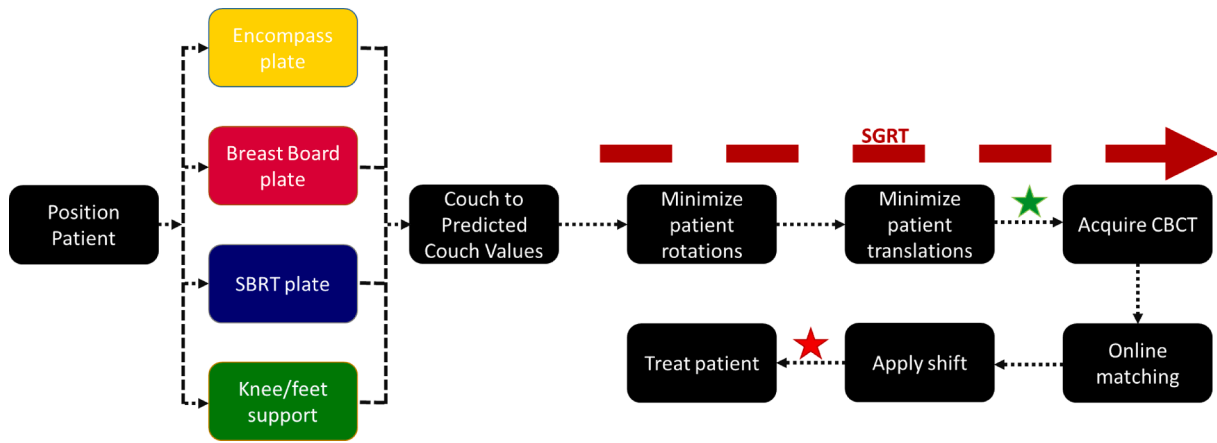| Pathology	Head/thorax	Knee	Feet
Brain	Encompass SRS Immobilization System + SRS Fibreplast thermoplastic mask (Qfix)	Cushion (no lock bar)	None
Lung (arms up)	ThoraxSupport (Macromedics)	Knee support (+lock bar)	Feet support (+lock bar)
Lung (arms down)	SBRT long base plate (Orfit) + grip pole	Knee support (+lock bar)	Feet support (+lock bar)
Prostate	Basic head cushion (no lock bar)	Knee support (+lock bar)	Feet support (+lock bar)

Fig. 1. Surface guided patient positioning workflow. Surface scanning is used during patient positioning to manually correct for patient rotations and to automatically correct for patient translations. The green star resembles the moment the actual couch parameters are used as reference to determine accuracy of the couch parameter prediction (ΔSetup). the red star takes into account patient's internal information (ΔTreat).
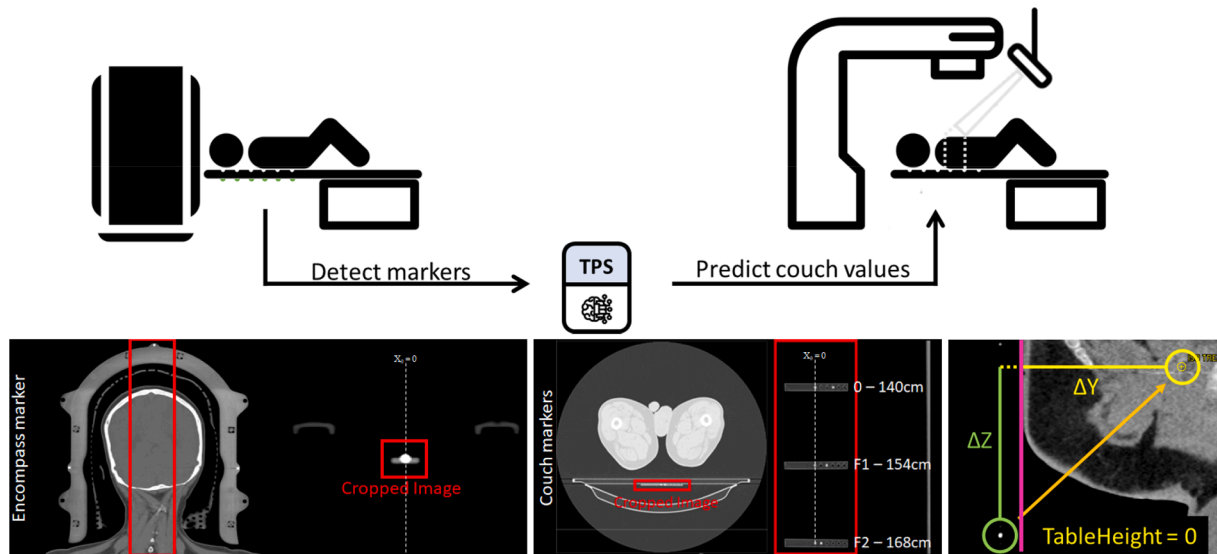

Fig. 2. Markers underneath CT couch top are detected via ML tool in the TPS and will be used to predict the couch parameters at the linac. The Transversal and coronal plane indicate the size of the cropped image and the positions of the Encompass and the couch markers. The most central markers align to the center of the image (X0 = 0). Based on a set of detected markers, linac couch parameters can be predicted.

couch values were acquired during the treatment delivery workflow (Fig. 1) and manually exported form the Aria database.

Based on these parameters, delta's and Euclidean distances were calculated:

$$\Delta \text{Setup}_{x,y,z} = P_{x,y,z} - S_{x,y,z}$$

$$\Delta \text{Treat}_{x,y,z} = P_{x,y,z} - T_{x,y,z}$$

$$d(\text{Setup}) = \sqrt{(P_x - S_x)^2 + (P_y - S_y)^2 + (P_z - S_z)^2}$$

$$d(\text{Treat}) = \sqrt{(P_x - T_x)^2 + (P_y - T_y)^2 + (P_z - T_z)^2}$$

$\Delta \text{Setup}_{x,y,z}$ is the delta between the predicted and the SGRT-based couch parameters (in x, y, z direction), where the latter are only based on patient's external information. On the other hand, $\Delta \text{Treat}_{x,y,z}$ also takes into account the internal patient information as it compares the predicted couch parameters against couch parameters obtained after CBCT matching (Fig. 1). Statistical analysis is performed in Python 3.9 using the SciPy and Pingouin packages.

Euclidean distance $d(\text{Setup})$ is calculated for all patients to calculate overall accuracy and to flag mild outliers, based on the interquartile range (IQR), when $d > Q_3 + 1.5*\text{IQR}$.

Results

For all patients, markers were detected at the correct position, notwithstanding a large variability in HU representing the marker's position ($\mu = 2050$, $\sigma = 765$). Couch parameters could be predicted with high precision ($\mu = 0.90 cm$, $\sigma = 0.92$) when compared against the SGRT-guided couch position, $d(\text{Setup})$. A trend towards slightly higher deviations is observed for $d(\text{Treat})$ (Fig. 3).

Based on the Euclidean distance $d(\text{Setup})$, 11 outliers were detected and excluded from the dataset if classified as incorrect index-position or incorrect position of head/knee/feet support. False positive outliers were not deleted from the dataset (Fig. 3).

Bell curves show ΔSetup in vertical, longitudinal and lateral direction (Fig. 4). In general, small baseline shifts between −3mm and + 2 mm were detected. A Bartlett's test of Homogeneity of Variances is used to test difference in variances. Additionally, one-way ANOVA revealed a
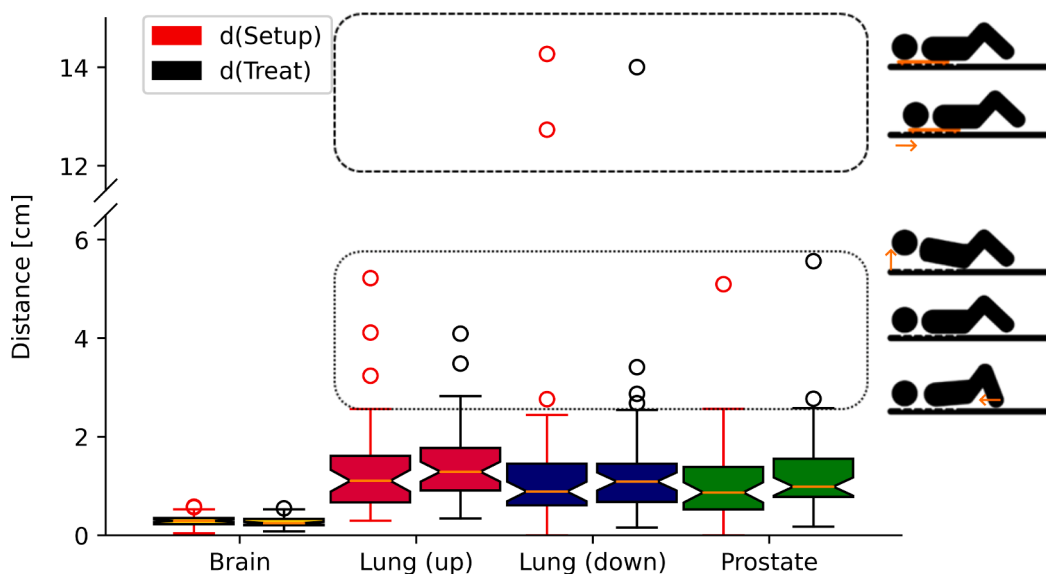
Fig. 3. Boxplots of both ΔSetup and ΔTreat for different pathologies and patient setups. Highest accuracy is obtained for brain patients in encompass base plate. The icons explain the outliers. incorrect index position or incorrect positioning of head/knee/feet support.
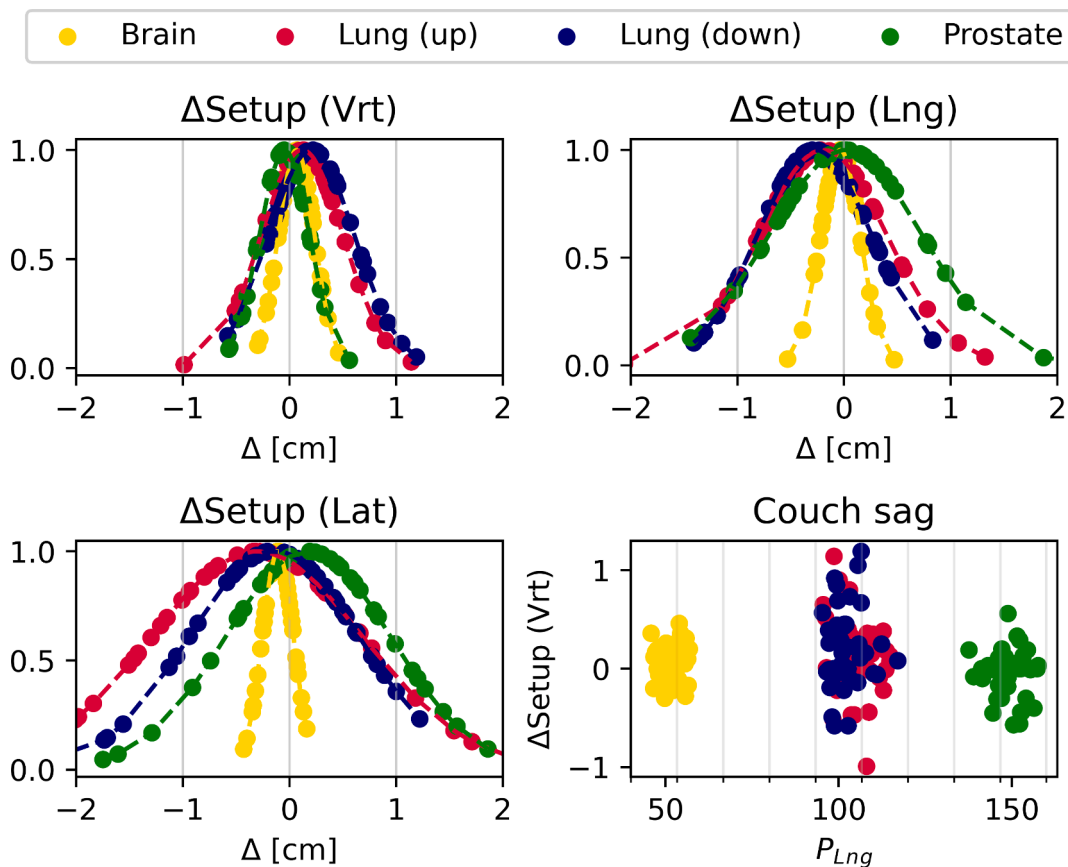

Fig. 4. Normalized bell curves show smallest error for prediction the vertical couch parameter. Overall, brain patients' couch parameter prediction is most accurate.

statistically significant difference in prediction accuracy, for all orientations, between at least two groups x: F = 3.17, p = 0.026, y: F = 5.10, p = 0.002, z: F = 3.04, p = 0.030. Tukey's HSD Test for multiple comparisons showed that the mean value of exam score was significantly different between Lung (arms down) and Prostate (p = 0.001, 95 % C.I. = [-0.43, −0.08]) in vertical direction and between Lung (arms up) and Prostate (p = 0.015, 95 % C.I. = [0.07, 0.89]) in lateral direction. No

statistically significant difference in mean was detected.

To investigate potential couch sag, $\Delta Setup_y$ was plotted as a function of P_z and Fig. 4 clearly shows no linear correlation.

Brain

The 58 d(Setup) samples display a median of 2.79 mm (IQR =

2.22–3.43) and four mild outliers are classified as false positive because very small IQR and confirmed by CBCT matching. The brain data reports the smallest median and IQR and this population will be used as a reference. The normal distribution, in each direction, of $\Delta\text{Setup}_{x,y,z}$[mm] has ($\mu = -1.00$, $\sigma = 1.46$), ($\mu = 0.61$, $\sigma = 1.68$), ($\mu = -0.19$, $\sigma = 1.89$) in respectively ×, y and z direction.

Lung

Lung (arms up) consists of 45 samples and has a median of d(Setup) of 11.06 mm (IQR = 6.67 – 16.11). The 44 samples of Lung (arms down) have a median d(Setup) of 8.88 mm (IQR = 6.07 – 4.51). Each group contains 3 outliers and two are classified as incorrect index position when $\Delta\text{Setup}_z \cong n*14\text{cm}(n \in \mathbb{Z})$, with 14 cm the exact distance between two notches in the couch top. Four outliers are related to incorrect positioning of head/knee/feet support. All six outliers are removed from the dataset. $\Delta\text{Setup}_{x,y,z}$[mm] reports ($\mu = -3.05$, $\sigma = 10.07$), ($\mu = 1.18$, $\sigma = 3.89$), ($\mu = -1.96$, $\sigma = 6.02$) in respectively ×, y and z direction for Lungs (arms up) data. Lungs (arm down) has following mean and standard deviation for ×, y and z: ($\mu = -1.45$, $\sigma = 8.08$), ($\mu = 2.08$, $\sigma = 4.08$), ($\mu = -2.76$, $\sigma = 5.40$).

Bartlett's test revealed a significant difference (p < 0.01) between the variances of Lung (arms up) and Brain and between Lung (arms down) and brain as summarized in Table 2.

Prostate

Out of a group of 43 samples, with a median d(Setup) of 8.68 mm (IQR = 5.24 – 13.86), only one outlier was detected and classified as incorrect positioning of knee/feet support. $\Delta\text{Setup}_{x,y,z}$[mm] reports ($\mu = 1.75$, $\sigma = 7.86$), ($\mu = -0.48$, $\sigma = 2.39$), ($\mu = 0.14$, $\sigma = 7.27$) in respectively ×, y and z direction.

No significant difference (p > 0.01) exist in ΔSetup_y. But, the variance of $\Delta\text{Setup}_{x,z}$ significantly differs between Prostate and Brain according to Bartlett's test.

Discussion

This ML based approach predicts, for all patients, independent of CT scanner or support device and fully automatically treatment couch parameters in support of SGRT-based patient positioning protocols. At the first treatment fraction, the prediction facilitates patient positioning as patient will first be moved to a reliable initial position which will be fine-tuned based on highly reliable SGRT information.

The ΔSetup metric will evaluate the couch parameter prediction accuracy in support of SGRT-based initial patient positioning as it only relies on patient's external (surface) information and the treatment isocenter. On the other hand, ΔTreat is additionally impacted by any internal anatomical patient change (Fig. 1). Nevertheless, ΔTreat allows to compare against other publications and provides additional information about the accuracy regarding the entire SGRT workflow which needs further research.

In depth CBCT analysis of all Lung patients revealed that deviations of d(Setup) > 1.5mm are related to suboptimal position of the support device. In case of perfect reproducibility of a patient's position, both patient anatomy and support device are in exactly the same position when comparing the CBCT image against the CT images. As online matching focusses on patient anatomy, offline review can show the discrepancy in support devices' position. When an offline deviation is found when comparing the position of the support devices (in case of perfect anatomy match), then the position of the support device was wrong during treatment (incorrect index position) or the patient was sub optimally positioned according to a perfectly placed support device (incorrect positioning of head/knee/feet support). The former is true when ΔSetup_z deviates a multiple of 14 cm, the exact distance between two notches in the couch top. More often smaller deviations are detected and are related to an incorrect position of head/knee/feet support, outside the treated area. In this case, the SGRT system tries to compensate for anatomical deviations close to the isocenter, based on an incorrect initial patient setup outside the SGRT scan region. For example, an incorrect position of a knee cushion might introduce a pitch and a longitudinal deviation in the scanned region of interest of the SGRT system. Consequently, larger patients' shifts are introduced while actually the patient is sub optimally positioned (Fig. 3, Fig. 5). For lung cases these deviations are introduced by incorrect position of indexed knee/feet support and correlate to deviations seen on CBCT when $\Delta\text{Setup}_{x,z} > 1.5$cm. For prostate patients, the head cushion is not indexed and prone to variations. On the other hand, brain patients are positioned in support of a rigid mask system which allows more accurate prediction and positioning[15].

Tukey post-hoc test for comparisons of means reveals no significant difference between brain and any other patient group, not in lateral, vertical or longitudinal direction. So on average prediction is similar, independent of pathology or support device. However, Bartlett's test shows the reference brain group has a significant smaller variance compared to any other group, except for ΔSetup_y between Prostate and Brain.

The larger deviations in the thoracic and abdominal region are not related to a more symmetric body shape in this area, because the couch parameter prediction minimizes this influence, nor to potential couch sag, but seems to be related to patient position accuracy and reproducibility. Improving the reproducibility of a patient's position between RT simulation and treatment by indexing all support devices (with lock bars) is key to increase accuracy of the couch parameter prediction and to optimize the SGRT-workflow. Alternatively, technological innovation like a thermal camera can also be used to tackle such issues[4]. Additionally, d(Setup) can be used as QA tool for patient positioning as deviations > 1.5 mm are related to incorrect position of support devices and not due to incorrect couch parameter prediction. In the latter case, it is recommended to double-check patient setup before finalising SGRT-guided patient setup.

Conclusion

The ML approach is able to detect markers and based on these detected points, couch parameters can be predicted with high accuracy suitable as starting point for SGRT-based patient positioning. Data shows that the used support devices or setup procedure impacts the predictive power of couch parameters. Moreover, the outlier detection based on d(Setup) IQR effectively detects outliers in case the interquartile range is not too small (brain IQR = 1.2 mm) and this parameter can be used as a QA tool for patient positioning: when the difference between the SGRT guided couch parameters and the predicted values exceeds the threshold of 1.5 cm, patient setup has to be verified (location of head/knee/feet support) and corrected before starting image acquisition and treatment delivery.

Table 2
P-values comparing homogeneity of variances using Bartlett's test.

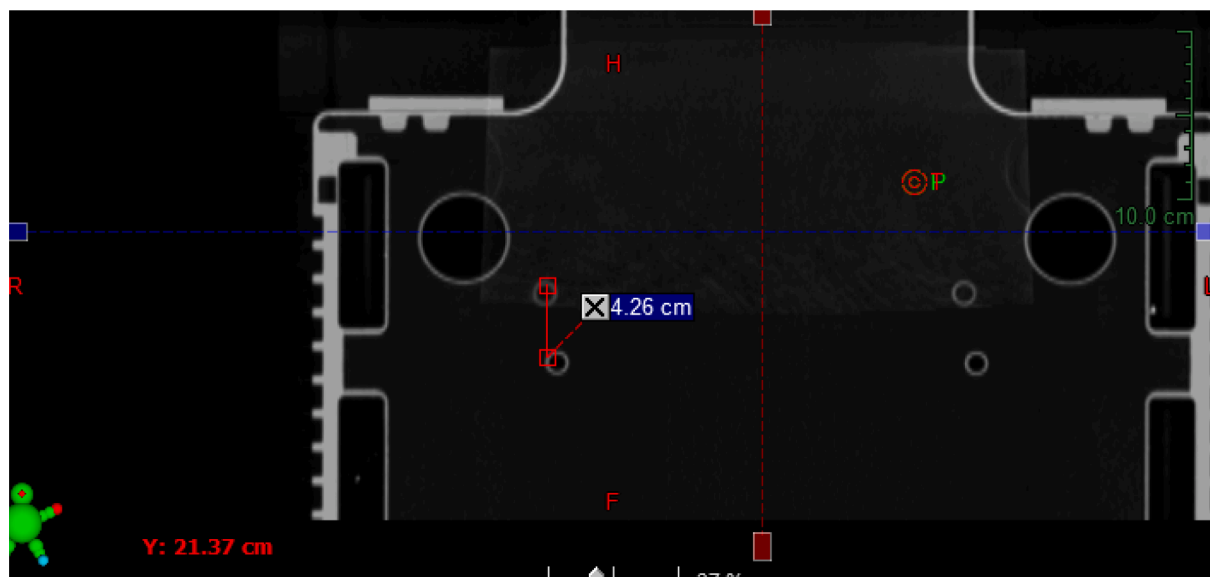|	Brain		
	X (Lat)	Y (Vrt)	Z (Lng)
Lung (arms up)	B = 136.43, p = 1.6e-31	B = 32.46, p = 1.2e-8	B = 58.72, p = 1.8e-14
Lung (arms down)	B = 112.71, p = 2.5e-26	B = 35.74, p = 2.2e-9	B = 48.96, p = 2.6e-12
Prostate	B = 110.30, p = 8.4e-26	B = 5.97, p = 0.016	B = 76.20, p = 2.6e-18

Fig. 5. In case of Incorrect positioning of knee/feet support offline review shows a difference of 4.26 cm when comparing the position of the support device itself. As this difference exactly equals ΔSetup, the deviation implies the patient is not positioned exactly the same as during ct simulation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Iridium Netwerk is involved in an on-going scientific collaboration with RaySearch Laboratories, C-RAD, Sun Nuclear Corporation and Sordina IORT Technologies.

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