Optimizing the patient positioning workflow of patients with Pelvis, Limb and Chest/Spine tumors at an ion gantry based on optical surface guidance

Abdallah Qubala MSc, Andrea Schwahofer Dr. sc. hum., Stefan Jersemann MSc, Saleh Eskandarian MSc, Semi Harrabi Dr. med., Patrick Naumann PD. Dr. Med., Marcus Winter Dr. rer. nat., Malte Ellerbrock Dr. rer. nat., Jehad Shafee BSc, Samira Abtehi MSc, Klaus Herfarth Prof. Dr. med., Jürgen Debus Prof. Dr. med. Dr. rer. nat., Oliver Jäkel Prof. Dr. rer. nat.

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[Article Full Title]
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[Author Names]
Abdallah Qubala\textsuperscript{1,2,3}, MSc
Andrea Schwahofer\textsuperscript{3,4}, Dr. sc. hum.
Stefan Jersemann\textsuperscript{1,3}, MSc
Saleh Eskandarian\textsuperscript{1,3}, MSc
Semi Harrabi\textsuperscript{1,3,5,6}, Dr. med.
Patrick Naumann\textsuperscript{1,3,5,6}, PD. Dr. Med.
Marcus Winter\textsuperscript{1,3}, Dr. rer. nat.
Malte Ellerbrock\textsuperscript{1,3}, Dr. rer. nat.
Jehad Shafee\textsuperscript{1,7}, BSc
Samira Abtehi\textsuperscript{1,3}, MSc
Klaus Herfarth\textsuperscript{1,3,5,6}, Prof. Dr. med.
Jürgen Debus\textsuperscript{1,3,5,6}, Prof. Dr. med. Dr. rer. nat.
Oliver Jäkel\textsuperscript{1,3,4,6}, Prof. Dr. rer. nat.

[Author Institutions]
1 Heidelberg Ion Beam Therapy Center (HIT), Heidelberg, Germany
2 Faculty of Medicine, University of Heidelberg, Heidelberg, Germany
3 National Center for Radiation Research in Oncology (NCRO), Heidelberg Institute of Radiation Oncology (HIRO), Heidelberg, Germany
4 Department of Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ), Heidelberg, Germany
5 Department of Radiation Oncology, Heidelberg University Hospital, Heidelberg, Germany
6 National Center for Tumor Diseases (NCT), Heidelberg, Germany
7 Saarland University of Applied Sciences, Saarbruecken, Germany

[Corresponding Author Name & Email Address]
Abdallah Qubala
abdallah.qubala@med.uni-heidelberg.de

[Author Responsible for Statistical Analysis Name & Email Address]
Abdallah Qubala
abdallah.qubala@med.uni-heidelberg.de

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[Ethics]
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Surface-guided radiation therapy, particle therapy, ion beam gantry, patient positioning workflow, patient setup time
1. Abstract

1.1 Purpose

Surface guided Radiotherapy (SGRT) has been intensively investigated to ensure correct patient positioning during a radiotherapy course. Although the implementation is well defined for photon beam facilities, only a few analyses have been published for ion beam therapy centers. To investigate the accuracy, reliability and efficiency of SGRT used in ion beam treatments against the conventional skin marks, a retrospective study of a unique SGRT installation in an ion gantry treatment room was conducted, where the environment is quite different to conventional Radiotherapy.

1.2 Methods and Materials

Thirty-two patients, divided into three cohorts: pelvis, limb, and chest/spine tumors, and treated with ion beams. Two patient positioning workflows based on 300 fractions were compared: workflow with skin marks, and workflow with SGRT. Position verification was followed by planar kV imaging. After image matching, six-degree corrections were recorded to assess inter-fraction positioning errors. Additionally, the time required for patient positioning, image matching, and the number of repeated kV imaging were also gathered.

1.3 Results

SGRT decreased the translational magnitude shifts significantly (p < 0.05) by 0.5±1.4 mm for pelvis, and 1.9±0.5 mm for limb, whereas for chest/spine increased by 0.7±0.3 mm. Rotational corrections were predominantly lowered with SGRT for all cohorts with significant differences in pitch for pelvis (p = 0.002), and chest/spine (p = 0.009). The patient positioning time reduced by 18 %, 9 %, and 15 % for pelvis, limb, and chest/spine, respectively, compared to skin marks. By using SGRT, 53 % of all studied patients had faster positioning time, and 87.5 % had faster matching time. Re-positioning and consequent re-imaging were dropped from about 7 % to 2 % with statistically significant difference of 0.042.
1.4 Conclusions

The quality of patient positioning prior to ion beam treatments has been optimized by using SGRT without additional imaging dose. SGRT clearly reduced inefficiencies in the patient positioning WF.

2. Introduction

The primary objective of radiation therapy is to deliver a prescribed dose to a tumor-bearing target volume as precisely as possible while sparing the adjacent healthy tissues to the furthest extent.\textsuperscript{1,2,3} This goal becomes more essential when utilizing tumor treatment approaches that involve using high doses with extremely steep dose gradients. Compared to photon beams, ion beams exhibit the advantage to deliver the same therapeutic dose to a deep located target with much less integral dose to the organs at risk due to Bragg-Peak and with increased biological effectiveness.\textsuperscript{1,4,5} One of the most difficult challenges for such a treatment technique is having a precise method for patient positioning in the entire course of therapy. Hence, it is ensured that deviations from the planned computed tomography (CT) are minimized.\textsuperscript{6}

Conventionally, the patient positioning process for ion beam treatments is based on planar kV imaging and/or CT,\textsuperscript{7} while cone-beam CT (CBCT) is limited to few institutions. At our institution, xxxx, we utilize in-room lasers (IRL) and permanent tattoos as skin marks for initial patient positioning and then verify the patient position with planar kV imaging per fraction. However, skin marks may cause a negative impact, especially on pediatrics and breast cancer patients, and potentially lead to psychological effects since the skin marks can serve as a reminder for the patients of their tumor treatments long after treatments.\textsuperscript{8,9,10} Moser et al.\textsuperscript{11} found that 70\% of women obtaining skin marks during the radiation therapy of breast cancer have bad feelings about the tattoos.

Furthermore, a disadvantage of employing skin marks for patient pre-positioning is that the skin marks on the elastic patient skin may be hard to find and align, e.g. in case of dark-colored skin and changes on the skin surface over the course of therapy.\textsuperscript{12} Therefore, the skin marks may deviate from the desired position, the accuracy may not be ensured and the patient has to be re-positioned.\textsuperscript{12}
Additionally, the main drawback of planar kV imaging (and to some extend also CBCT) is that position variations can only be assessed and verified using bony landmarks, irrespective of changes in water equivalent thickness along the beam path (e.g. tissue swelling, effusion, changes in tumor size). Such an approach is unable to precisely match and consider anatomical changes owing to soft tissue variations. This may result in inaccuracies, leading to an altered dose distribution within the target volume and organs at risk. As a supplementary method, a control CT image may be used, but will not be evaluated directly or performed frequently since only one CT scanner is available in one of our treatment rooms for position verification at xxxx, and also due to concerns about the additional imaging dose, particularly in case of pediatric patients.

The demand of nonionizing skin-based image guidance which relies on the patient skin surface but not only on three skin marks is needed.\textsuperscript{13} For this purpose, a surface guided radiation therapy (SGRT) system (VisionRT\textsuperscript{®} Ltd., London, UK) combined with a unique mounting structure frame has been installed in the isocentric ion beam gantry of our institution. SGRT may support the initial patient positioning without any additional dose, and can track the position of the patient during the whole irradiation time.\textsuperscript{14} Furthermore, SGRT may supply faster and a more precise patient positioning compared to skin marks.\textsuperscript{15} For this aim, it compares the current patient skin surface and the reference patient skin surface from the planning CT data within a user-defined region of interest (ROI).\textsuperscript{16}

The aim of this retrospective study is firstly to quantify the reliability, accuracy and efficiency of SGRT in positioning of patients prior to planar kV imaging in comparison to skin marks based patient positioning. Secondly, it shall be investigated, if SGRT can improve workflow (WF) efficiency by reducing the patient setup time (positioning and image matching), and the frequency of incorrect positioning (immobilization setup errors). Finally, it shall be observed, whether repeated planar kV imaging during patient positioning may be reduced.
3. Methods and Materials

3.1 Gantry treatment room at xxxx

xxxx operates three treatment rooms. Two rooms deliver the beam in fixed horizontal direction, and the third one is an isocentric gantry with a length of 25 m, a diameter of 13 m, and the ability to rotate around 360 ° (Figure 1). Despite of considerable mass of the gantry (660 tons), accuracy of less than one millimeter in beam position is achievable. Proton, Carbon, and Helium ions can be delivered at the gantry.5 Indications such as craniospinal irradiation, focal irradiation of head and neck or brain tumors, lymphoma, prostate cancer, skull base and spinal sarcoma are treated. Planar kV imaging is utilized for patient position verification and final alignment at the gantry.

3.2 SGRT system

In this Study, the AlignRT® software version 5.1.2. developed by VisionRT® Ltd. (London, UK) was used. Owing to the special construction of our ion gantry treatment room, a standard installation of a SGRT system was not possible due to the moveable ceiling of the gantry while gantry rotation, the size of the beam nozzle, and the foldable floor in the rotation area of the gantry (Figure 1). Thus, an individual mounting was created by a third-party company (S. Bleyer GmbH, Schorndorf, Germany). This spiderweb-like structure frame was screwed directly to the gantry bearing enabling optimal 3D data acquisition by avoiding (i) transfer of gantry rotation movements into the system and (ii) shading of the optical system by the beam nozzle. The system hardware consists of three camera pods mounted to the gantry bearing, each with two image sensors and a projector that displays an optical random speckle pattern on body surface of patient. The AlignRT® software is able to calculate position deviations, the so-called real time deltas (RTDs) for three translations (vertical, longitudinal and lateral) and three rotations (iso, roll, and pitch). For the calculation, a user-defined ROI (Figure 1) and a rigid-body transformation between the reference surface and the current surface of the patient is used. The calculation is based on active stereo photogrammetry and triangulation.16,17,18,19
The system was inspected through conducting a yearly basis specialized quality assurance (QA) program comprised of monthly calibration, WF test, and gantry angle dependency tests to ensure that all components in the room, such as robotic treatment table, robotic imager, IRL, gantry and SGRT system interacted properly. Additionally, relative to the monthly reference calibration, the position of the pods was monitored based on daily QA prior to therapy start.

### 3.2.1 SGRT system accuracy

The positioning accuracy of the AlignRT® system at xxxx has been over the technical commissioning and evaluation phase thoroughly investigated, and is briefly presented here. By using the planning CT, the absolute positioning accuracy of the SGRT system compared to planar kV imaging system for the Quasar™ phantom developed by Modus QA (London, Canada) and the virtual human male CIRS pelvic phantom developed by CIRS (Norfolk, USA) was examined. For the Quasar phantom, the average translational differences between AlignRT® and planar kV imaging were -0.1±0.2 mm in lateral, -0.2±0.3 mm in longitudinal, and -0.3±0.2 mm in vertical direction, respectively. The average rotational discrepancy was 0.0±0.2 ° in iso, -0.0±0.1 ° in pitch and 0.0±0.1 ° in roll. For the CIRS-Pelvis phantom, deviations of 0.2±0.1 mm in lateral, -0.3±0.4 mm in longitudinal and 0.0±0.3 mm in vertical direction as well as -0.1±0.1 ° in iso, 0.2±0.2 ° in pitch and 0.0±0.3 ° in roll were recorded. Furthermore, the tracking accuracy of the AlignRT® system in the isocenter was tested relative to a 3D FARO® laser tracker developed by Modus QA (Lake Mary, USA) by moving the treatment table to pre-defined translational and rotational coordinates. The CIRS-Pelvis phantom was used for this test. The maximum differences between AlignRT® computations and calculated values of the laser tracker were 0.01±0.01 mm in translation (± 100 mm for each translation), and 0.0±0.2 ° in rotation (± 5 ° for each rotation).

### 3.2.2 ROI design

The aim of drawing a ROI is to focus the six degrees of freedom (6DOF) match on a surface region, which can provide more relevant and precise surface tracking. This depends on the SGRT system application. In order to draw an appropriate ROI on the reference patient skin surface, it was required to obtain so-
called reference captures utilizing AlignRT® at the first treatment fraction to observe which portions of the patient surface are processed owing to limitations e.g. shadowing of camera by the beam nozzle. The reference capture in AlignRT® is defined as an option to take a new reference of the current patient position. This capture differs from the reference surface reconstructed from the planning CT data, and was merely used for an optimized ROI definition on the planning CT (Figure 1). The planning CT used as reference is called DICOM reference surface, “Digital Imaging and Communication in Medicine”. Figure 1 shows the optimized ROIs using the reference captures.

3.3 Treatment Planning System (TPS)

The patient plan data produced by the TPS utilizing the planning CT are required for SGRT. The RayStation TPS (RS10A, RaySearch Laboratories, Stockholm, Sweden) was used for contouring at xxxx. The lower Hounsfield units (HU) thresholds used for the contouring of the reference skin surface in planning CT were ranged from -250 HU to -350 HU and the upper thresholds ranged from 1500 HU to 3071 HU depending on the patient anatomy.

3.4 Study design

This study was conducted in two WFs for initial patient positioning prior to planar kV imaging: WF with skin marks, and WF with SGRT. 32 patients were included and divided into three cohorts: pelvis, limb and chest/spine (Table 1). The first 8 to 10 treatment fractions of each patient were evaluated, and accordingly the statistical analysis was performed based on 300 fractions. The two WFs were compared for each patient. To keep the overall treatment time and study related patient burden as low as possible, the SGRT WF was performed not on a daily basis but 2-3 times a week. The following parameters were analysed: the translational and rotational residual shifts of patient position based on kV image matching, the total setup time required for patient positioning including matching time, and the so-called re-imaging frequency including number of repeated planar kV imaging and re-positioning for final confirmation.
Patient and setup specifications including tumor region, matching bony landmarks for planar kV imaging, immobilization devices and patient posture in the planning CT are introduced in Table 1. All patients obtained a free-breathing planning CT with 3 mm slice thickness.

3.4.1 Clinical WF: Skin marks vs. SGRT

For both WFs (Figure 2), the patient was initially moved with the 6DOF robotic treatment table\(^{30}\) from a step-on position to so-called reference point in our WF (isocenter) at gantry angle of 0 ° using the hand held control. The skin marks and the IRL are used for patient pre-positioning in the WF with skin marks.

The AlignRT\(^{®}\) was used for aligning the patient in the WF with SGRT instead of the skin marks and IRL. Subsequently, the patient moved to the imaging point which is previously defined by the radiotherapist, relative to the reference point. The reference point is determined by the skin marks and deemed to be the reference for all later points (imaging point and beam isocenter points). The imaging point is qualified as the position verification of the patient using bony landmarks and it can differ from reference and beam isocenter points.

In the WF with SGRT, patients were initially positioned relative to the DICOM reference surface using AlignRT\(^{®}\) real-time imaging and pre-defined thresholds of 3 mm for translations and 2 ° for rotations for all regions in both reference and then imaging point if the imaging point is not equal to the reference point. The so-called treatment captures in AlignRT\(^{®}\) were captured twice, after both positioning in the reference point and in the following imaging point. Treatment captures are snapshots of the patient for documentation purposes and can be performed either static or gated depending on the region. The corresponding RTDs in the imaging point were collected only, but not applied for patient pre-positioning since the treatment machine is not connected to the AlignRT\(^{®}\) system. The final patient position was verified through planar kV imaging including anterior-posterior (AP) and left-right (LR) images in both WFs. The bony landmarks in the imaging point region was used to match the planar kV images acquired in AP and LR with the digitally reconstructed radiographs (DRR). The DRRs were generated from the projections of the planning CT series projected to a 2D plane (Table 1). After the kV matching process,
rotational and translational correction vectors were applied to precisely position the patient at the beam isocenter point(s). The later correction vectors were compared with the remaining offsets indicated by the AlignRT®.

The matching process of the first fraction was always evaluated through the physician in charge and during the remaining fractions by the therapists. If the post-kV imaging adjustments in both WFs, in translations and/or rotations, exceeded the position correction constraints, which are dependent on the treated indication and employed setup devices, the entire WF was repeated from the beginning including re-positioning and re-imaging. In our workflow protocol, the criteria for re-positioning are defined by the physician regarding the ALARA principle, “as low as reasonably achievable”, and by the medical physicist regarding collision constraints in the treatment room resulting dose effects (i.e. moving material edges into the beam path), and movement limits of the treatment couch robot.

3.4.2 Data collection and statistical analysis

Patient data was collected between May 2020 and December 2021 as part of the clinical routine and reviewed for this retrospective study. To assess the reliability, accuracy and efficiency of SGRT in detection and quantification, all position deviations calculated by AlignRT® following treatment capture were reviewed for each patient treatment fraction. All kV image matching correction vectors applied in the imaging points after both WFs were also recorded by the treatment machine. The average (μ) and the standard deviation (SD) were calculated for all studied treatment fractions. The resulting residual setup imaging correction vectors were divided into two kinds of setup error which were defined by Bijhold et al.21 and de Boer et al.22: cohort residual systematic setup errors (Σ), and cohort residual random setup errors (σ). The Σ corresponds to the standard deviation of all patient averages and σ corresponds to the average of all standard deviations. The time spent on patient positioning and kV image matching was recorded, separately. The additional time for repeating the patient setup workflow including re-positioning and re-imaging is not included in this work but it usually takes several minutes that it should be taken to account. The number of repeated planar kV images when re-positioning the patient was also documented. The statistical analysis was performed using SPSS software (IBM, New...
York, USA). Statistical differences of the residual corrections of two WFs were evaluated using paired Wilcoxon signed-rank test and, correlation tests were evaluated using the Spearman tests. Results were considered significant when p-value < 0.05.

4. Results

4.1 Patient characteristics

We assessed 32 patients with mostly tumors of pelvis, limb, and also tumor locations in the chest and spine. Patient characteristics are depicted in Table 1.

4.2 Reliability and accuracy of patient positioning: Skin marks vs. SGRT

Comparison of SGRT versus skin marks in patient positioning prior to treatment for 32 patients, a total of 300 fractions, was analysed. The translational and rotational residual µ, Σ and σ setup errors for each cohort following kV image matching are shown in Table 2. The p-values for all residual corrections of translations and rotations are also demonstrated in Table 2. Additionally, cumulative histograms showing the residual magnitude of post-imaging 3D correction vectors for both WFs, skin marks and SGRT, for three cohorts are introduced in Figure 3.

4.3 Positioning and matching time: Skin marks vs. SGRT

The average time and the standard deviation recorded for the positioning and kV image matching process for each patient in both WFs are introduced in Figure 3. The irradiation time is not included. Additionally, the total setup time including the positioning on the treatment table and kV image matching was as following with statistically significant differences of time by 0.018 and 0.023 for pelvis and chest/spine, respectively, while in limb patients a non-significant shortening of total setup time was observed (p = 0.05):

I. Pelvis cohort: 05:57±02:11 (mm:ss) for skin marks vs. 04:54±01:06 (mm:ss) for SGRT

II. Limb cohort: 05:39±02:12 (mm:ss) for skin marks vs. 05:09±01:34 (mm:ss) for SGRT
III. Chest/Spine cohort: 06:09±02:26 (mm:ss) for skin marks vs. 05:15±01:30 (mm:ss) for SGRT

4.4 Frequency of re-imaging required prior to treatment: Skin marks vs. SGRT

Another component of the analysis included the assessment of re-imaging frequency. Re-imaging means, as mentioned previously (Figure 2), not only repeating the positioning WF but also more ionizing dose for the patient. Thus, the entire treatment WF efficiency is heavily dependent on the positioning process. Figure 3 depicts the total number of re-imaging performed for each patient during the assessed number of the 8 to 10 fractions. By Using SGRT for patient positioning, the re-imaging frequency dropped from about 7 % to 2 % with statistically significant difference of 0.042.

5. Discussion

The initial patient positioning prior to treatment, merely based on three skin marks (i.e. tattoos), which must be found by the therapists, is still not adequate enough for avoiding patient setup inefficiencies, especially in torsions. Additionally, existing tattoos from previous radiation therapies may be confused with the marks of the actual treatment. In case of dark-colored or heavily freckled skin, hair follicles and moles may be mistaken with tattoos due to similar appearance, resulting in a potential patient setup errors. Furthermore, it is usual for therapists to shift the skin surface to align the tattoos with IRL without changing the position of the internal anatomy. These pitfalls highlight the need for improvements in initial patient setup, since repeating the whole patient positioning process, including planar kV imaging, exposes the patient to more radiation. This can delay therapy, generates stress for both patient and treatment team, and extends the patient’s treatment period. These inefficiencies could be minimized by implementing SGRT as a complementary for planar kV imaging for more accurate positioning.

Previous studies in conventional radiotherapy using a linear accelerator have investigated the reliability, stability and reproducibility of different SGRT systems for setup and intra-fraction motion monitoring during radiation therapy treatments of abdomen, pelvis, extremity, chest, head and neck. These studies focus on techniques like stereotactic radiosurgery (SRS),...
sleeve body radiotherapy (SBRT) and deep inspiration breath hold (DIBH) in the photon beam treatments, and the final patient position mostly verified by CBCT which is not available in our ion gantry treatment room. They showed that the use of nonionizing SGRT may replace the skin marks, provide more accurate initial patient positioning than skin marks prior to CBCT or planar kV imaging, and also enable more secure intra-fractional monitoring than the WF with skin marks. Furthermore, the total setup time when using the SGRT can be shorter than WF with skin marks.27,28,31,32

Our study design focusses on using AlignRT® system to optimize patient positioning WF in a unique treatment room, where the environment is quite different to conventional RT due to considerably large size of treatment machine and treatment room. Although the implementation is well defined for photon beam facilities, only a few analyses have been published for ion beam therapy centers. Batin et al.31 investigated the setup accuracy of SGRT and a traditional planar radiographic technique for postmastectomy chest wall patients treated with proton therapy. They found that SGRT provided both more accurate and faster patient setups compared to conventional radiographic setup technique. The results of this study confirm these findings and extend them for further body regions. However, this study provides no points over the correlation between both skin marks and SGRT. Finally, the reliability, accuracy and efficiency of optical surface imaging will be discussed in this study by comparing both WF schemes, skin marks and SGRT, based on investigations of three patient cohorts, pelvis, limb, and chest/spine.

5.1 Reliability and accuracy of patient positioning: Skin marks vs. SGRT

Our investigation indicates that the use of SGRT significantly decreases the cohort translational couch magnitude shifts during patient setup by 0.5±1.4 mm for pelvis patients, and by 1.9±0.5 mm for limb patients (p < 0.05), whereas for chest/spine patients SGRT significantly increases the magnitude shifts by 0.7±0.3 mm (p = 0.001). The reason for the later finding is probably the free-breathing CT scans used for chest/spine treatment planning, which are affected by the interplay between scanning in the CT and free-breathing. Thus, the current position constantly deviates from the reference position, particularly in vertical, longitudinal and pitch errors. Table 2 shows that rotational corrections were predominantly
lowered with SGRT for all cohorts with significant differences in pitch for pelvis ($p = 0.002$), and chest/spine ($p = 0.009$).

The reliability of SGRT to more accurately position the patient may be attributed to several factors. Skin marks utilize the positions of only three points on the skin surface, whereas SGRT uses a 3D ROI that covers nearly the entire treated region for surface matching. This study also shows that SGRT reduced most translational and rotational systematic and random errors, since positioning using the skin marks is more affected by circulation of personnel and individual experiences for each patient. The WF steps using SGRT are more consistent for every patient and less dependent on the personnel if the therapists’ team is well trained. In our center, 85 % of our therapists’ team have more than a year, and 61 % more than three years’ experience with SGRT system. Furthermore, the SGRT WF can potentially replace the IRL for these three cohorts investigated in this study.

### 5.2 Positioning and matching time: Skin marks vs. SGRT

Using SGRT resulted in a considerable reduction in total patient setup time (positioning and matching time) in our investigation. SGRT-based positioning prior to treatment required 18 %, 9 %, and 15 % less time for the entire setup procedure for pelvis, limb, and chest/spine patients, respectively, than with the skin marks positioning approach. Furthermore, the standard deviation by employing the SGRT system eased off on average of 49 %, 29 % and 38 % for pelvis, limb, and chest/spine patients, respectively. This later finding implies that the initial patient positioning became more resilient against setup inefficiencies. Our data have also shown strong correlation, $0.001 < P < 0.045$ for SGRT, and $0.001 < P < 0.011$ for skin marks between positioning time and matching time. Finally, 53 % of all studied patients had faster positioning time, and 87.5 % had faster matching time by using SGRT compared to skin marks (Figure 3). Moreover, this can be even improved if the initial position is automatically corrected using SGRT.
5.3 Frequency of re-imaging required prior to treatment: Skin marks vs. SGRT

The data shows a clear reduction of re-imaging frequency when SGRT was used for the initial patient positioning of pelvis and chest/spine patients (Figure 3). This indicates potentially a more consistent WF. The higher re-imaging frequency at pelvis and chest/spine compared to limb is related to the different immobilization methods. While most pelvis and chest/spine patients are immobilized using ProSTEP™, HeadSTEP™, WingSTEP™ enabling more mobility, using the skin marks in this case only is not sufficient to detect rotational setup errors, especially pitch and roll. On the other hand, all limb patients are immobilized using BlueBAG™ vacuum cushions with less mobility compared to pelvis and chest/spine immobilization approaches. However, SGRT is particularly helpful to position limbs.

The reason for the re-imaging in the WF with SGRT is related to non-sufficient experiences by drawing an appropriate ROI which may distort the true position of the patient. Thus, it is recommended to use more than one ROI during the positioning process.

5.4 Potential role of SGRT for detecting anatomical changes

Large discrepancies between skin marks and SGRT, or planar kV imaging and SGRT may potentially serve as an indicator for anatomical changes (e.g. weight fluctuations or tissue swelling). Even though, the capability of SGRT to possibly detect anatomical changes on the skin surface in the area of the anterior beam entry should be investigated and confirmed for ion beam therapy by future studies, since ion beam treatments are more sensitive to changes in water equivalent thickness in beam entry path compared to photons due to Bragg-Peak which may lead to an altered dose distribution within the target volume and organs at risk.

A chondrosarcoma was an example of anatomical changes in our investigation. The tumor showed a growth by about 1 cm in the beam entrance region by initially using SGRT. There were significant differences between planar kV imaging and SGRT in position. This was confirmed through a comparison between the regular control CT and the original planning CT. The irradiation plan had to be adapted using a new planning CT (Figure 4). Another example of postoperative edema in the lower extremity at the time of planning CT was regredient in the interval of 11 days between planning and initiation of
treatment. The reconstructed soft tissue was registered to the original planned CT using a regular control CT determined a decrease by roughly 6-8 mm. These anatomical modifications had no effect on the irradiation. In this scenario, no re-planning was necessary.

Finally, the main disadvantage of using skin marks for patient positioning prior to treatment, is that the skin marks on the elastic patient skin might undergo significant deviations over the course of therapy due to anatomical changes which may be detected by comparing both reference and current patient skin surface in AlignRT® system on a daily basis. That would be a very important benefit for particle therapy centers where is no CBCT available.

5.5 Limitations and considerations of SGRT

The gantry construction, the large beam nozzle, patient geometry, and immobilization devices obscured and reduced the Field of View (FOV) of the three AlignRT® pods in numerous instances. This resulted in unprocessed surface regions where the system is unable to acquire surface data. The position of the three pods was optimized prior to settling on a compromise position that resulted in reduced obstruction by the beam nozzle and sufficient FOV for patient positioning.

The inability to scan very dark skin tones, which results in surface degradations that look as holes, is another unavoidable technical constraint of using SGRT. This is crucial for institutions that serve a higher number of patients with darker skin tones.33

Additionally, the AlignRT® system in xxxx is not connected to the treatment table, which is a significant difference from a typical LINAC setup. As a result, the computed shifts of AlignRT® require to be adjusted manually by moving the treatment table using the hand control. Thus, we assume that a direct feedback of the SGRT system to the treatment table may result in further decrease in residual setup errors, improved setup accuracy and faster positioning process prior to treatment.

Further limitation of utilizing SGRT to analyse patient position deviation is the ability to exclusively evaluate visible patient skin surface to the pods. In this case, brain and head-and-neck patients with
thermoplastic mask can benefit from SGRT by using open-face or minimal mask immobilization which were investigated in previous studies.24,27,28

6. Conclusion

We found that employing SGRT as a complementary for planar kV imaging can optimize the patient positioning WF and can increase the positioning accuracy prior to tumor treatments of pelvis, limb and chest/spine patients without extra imaging dose. Based on our data, using SGRT for patient positioning considerably reduced the total setup time, re-imaging frequency, and enhanced the WF efficiency. Thus, the reliability of our unique SGRT installation is confirmed for patient positioning. We also found that a good ROI design can lead to a more robust patient positioning using SGRT. In addition, this SGRT system will be used for other purposes, e.g. intra-fractional irradiation monitoring and gating methods. Furthermore, SGRT may also provide the ability to detect anatomical changes in anterior beams regions that potentially influence dose distribution in CTV and OARs, particularly in superficial target volumes where the internal target potentially correlates with the patient skin surface. The correlation between the internal target and the external skin surface, which is influenced by several factors such as tumor location, age, gender and body mass index should be investigated using SGRT to use the full benefits of SGRT.
References

1. xxxx. (anonymised)

2. xxxx. (anonymised)


4. xxxx. (anonymised)

5. xxxx. (anonymised)


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Declaration of interests

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.
Figure captions

Figure 1: Gantry treatment room at xxxx including beam nozzle at 240 ° (a), robotic treatment table (b), foldable floor (c), and SGRT system installation (d) including three AlignRT® pods on the left picture. On the right side, different immobilization setups at the planning CT with different ROIs dependent on the indication and patient anatomy for pelvis patient positioned using ProSTEP™ (e), limb patient positioned using BlueBAG™ vacuum cushion (f), chest patient positioned using WingSTEP™ (g), and spine patient positioned using BlueBAG™ vacuum cushion and thermoplastic mask (h). Source: xxxx. ProSTEP™, HeadSTEP™, WingSTEP™ and BlueBAG™ vacuum cushions are developed by Elekta (Stockholm, Sweden).

Figure 2: WF explanation. (a) WF with skin marks. (b) WF with SGRT. Abbreviations: RP = reference point; IRL = in-room-laser; SM = skin marks; PP = patient positioning; IP = imaging point; SG = surface guidance; TC = treatment capture.
Figure 3: Cumulative histograms showing the residual post-imaging 3D correction vectors (a-c), summary of positioning average time, kV image matching average time and standard deviation (d-f) for the skin marks as well as SGRT method, and re-imaging frequency for all investigated patients pelvis (P1-11), limb (L1-11) and chest/spine (C1-10), respectively. Abbreviations: P = pelvis; L = limb; C = chest/spine.
Figure 4: Dose distribution degradation caused by tumor growth, about 1 cm during the treatment course of a chondrosarcoma patient and confirmed by the control CT. The left upper figure (a) illustrates the planning CT including the contouring of the skin surface and clinical target volume (CTV) and the left lower figure shows the tumor growth on the control CT after four irradiated fractions. The right lower figure (b) illustrates the shifted dose distribution on the control CT transferred from the original plan (right upper). Source: xxxx.
### Tables

Table 1: Patient and setup specifications. *analysed fractions distributed equally for each WF.

<table>
<thead>
<tr>
<th>Site &amp; Patient number</th>
<th>Median age (min-max)</th>
<th>Diagnosis</th>
<th>Immobilization</th>
<th>Matching bony landmarks</th>
<th>Fractions analysed* (total treated fractions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis P1-11</td>
<td>50 (18-86)</td>
<td>7 sarcomas</td>
<td>10 ProSTEP™</td>
<td>Hips, Coccyx, Femur, Spine</td>
<td>100 (248)</td>
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<tr>
<td></td>
<td></td>
<td>4 chordomas</td>
<td>1 BlueBAG™</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limb L1-11</td>
<td>41 (14-73)</td>
<td>11 sarcomas</td>
<td>11 BlueBAG™</td>
<td>Knee, Tibia, Femur, Hips</td>
<td>100 (230)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chest/Spine C1-10</td>
<td>24.5 (9-80)</td>
<td>7 sarcomas</td>
<td>3 WingSTEP™</td>
<td>Sternum, Spine, Vertebral body</td>
<td>100 (235)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 lymphomas</td>
<td>4 BlueBAG™</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3 HeadSTEP™</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Thermoplastic masks</td>
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Table 2: Residual setup post-imaging correction vectors after patient pre-positioning using both WFs for all patient cohorts (at \( \alpha = 0.05 \) significance level). Abbreviations: \( \mu \) = cohort average; \( \Sigma \) = cohort residual systematic setup error; \( \sigma \) = cohort residual random setup error; LAT = lateral correction; LNG = longitudinal correction; VRT = vertical correction; Mag = Magnitude.

<table>
<thead>
<tr>
<th>Site</th>
<th>Skin marks</th>
<th>SGRT</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>( \mu )</td>
<td>( \Sigma )</td>
<td>( \sigma )</td>
<td>( \mu )</td>
<td>( \Sigma )</td>
<td>( \sigma )</td>
</tr>
<tr>
<td><strong>Pelvis</strong></td>
<td>LAT (mm)</td>
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<td>2.6</td>
<td>3.7</td>
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</tr>
<tr>
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<td>LNG (mm)</td>
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<td>-0.7</td>
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<tr>
<td></td>
<td>VRT (mm)</td>
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<td>3.4</td>
<td>2.2</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Mag (mm)</td>
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<td>2.3</td>
<td>3.8</td>
<td>6.6</td>
<td>2.3</td>
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<tr>
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<td>0.4</td>
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<tr>
<td></td>
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<td>1.1</td>
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<td>1.2</td>
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<tr>
<td></td>
<td>Roll (*)</td>
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<td><strong>Limb</strong></td>
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<tr>
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<td>VRT (mm)</td>
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