

Clinical implementation of a rotating pod for lung tumor in fixed ion beam lines

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Date: 2025-02-05T00:00:00+00:00

Abstract

The purpose of this study was to evaluate the clinical application of a rotating pod and assess its dosimetric considerations, positional accuracy, and anatomical structure stability. A pre-dosimetric study conducted on 11 patients revealed the potential for lung dose reduction using the rotational pod. Subsequently, seven patients underwent treatment with the rotational pod, and the target coverage and organs at risk doses were compared with those of conventional methods. The positional accuracy of the rotational pod, in collaboration with the imaging guidance system, was analyzed. The Dice similarity coefficient (DSC) was used to assess the settlement of tumors, trachea, and thoracic vertebrae after rotation for 20 min. In the pre-dosimetric study, there was no statistically significant difference in the internal gross tumor volume receiving $\geq 99\%$ of the prescription dose between the pod and conventional couch plans. However, compared to conventional couch plans, pod plans demonstrated a significant reduction in the average lung dose by 5%-53% ($p < 0.01$). Patient accrual, comprising seven cases, revealed reduced lung doses (9%-26%) in four patients. For the other three patients, although there was no significant reduction in the lung dose, the use of the 90° beamline contributed to a decrease in the patient admission waiting time. The positional errors between the beams for lateral, longitudinal, vertical, ISO, pitch, and roll directions were $0.0 \text{ mm} \pm 5.3 \text{ mm}$, $-1.2 \text{ mm} \pm 2.3 \text{ mm}$, $-1.1 \text{ mm} \pm 2.7 \text{ mm}$, $0.0^\circ \pm 0.6^\circ$, $-0.1^\circ \pm 0.5^\circ$, $0.0^\circ \pm 0.8^\circ$, respectively. The DSC for the target region and thoracic vertebrae between CT images captured before and after a 20-min rotation was higher than 0.85, whereas the DSC for the trachea was approximately 0.8. The preliminary clinical application of the rotational pod for lung tumors in fixed-ion beam lines shows promise for achieving target coverage, reducing lung dose, and maintaining position accuracy.

Full Text

Preamble

Clinical Implementation of a Rotating Pod for Lung Tumor in Fixed Ion Beam Lines

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This study evaluated the clinical application of a rotating pod, assessing its dosimetric performance, positional accuracy, and anatomical structure stability. A pre-dosimetric study of 11 patients demonstrated potential lung dose reduction using the rotational pod. Subsequently, seven patients were treated with the rotational pod, and target coverage and organ-at-risk (OAR) doses were compared with conventional methods. Positional accuracy of the rotational pod in conjunction with the imaging guidance system was analyzed. The Dice similarity coefficient (DSC) was used to assess the settlement of tumors, trachea, and thoracic vertebrae after 20 minutes of rotation.

In the pre-dosimetric study, no statistically significant difference was observed in the internal gross tumor volume receiving 99% of the prescription dose between pod and conventional couch plans. However, compared to conventional couch plans, pod plans demonstrated a significant reduction in average lung dose by 5%-53% ($p < 0.01$). Clinical data from seven patients revealed reduced lung doses (9%-26%) in four patients. For the remaining three patients, although no significant lung dose reduction was achieved, the use of the 90° beamline substantially decreased patient admission waiting time. Positional errors between beams for lateral, longitudinal, vertical, ISO, pitch, and roll directions were $0.0 \text{ mm} \pm 5.3 \text{ mm}$, $-1.2 \text{ mm} \pm 2.3 \text{ mm}$, $-1.1 \text{ mm} \pm 2.7 \text{ mm}$, $0.0^\circ \pm 0.6^\circ$, $-0.1^\circ \pm 0.5^\circ$, and $0.0^\circ \pm 0.8^\circ$, respectively. The DSC for target region and thoracic vertebrae between CT images captured before and after a 20-min rotation exceeded 0.85, whereas the DSC for the trachea was approximately 0.8. Preliminary clinical application of the rotational pod for lung tumors in fixed ion beam lines shows promise for achieving target coverage, reducing lung dose, and maintaining positional accuracy.

Keywords: Rotational pod, Carbon ion radiotherapy, Lung cancer, Position accuracy

Introduction

A well-optimized plan for ion radiotherapy can frequently be attained using no more than four beam-entry angles achieved through rotation of the gantry, rotation of the patient positioning table, or a combination of both. The selection of these angles is pivotal for achieving the prescribed target dose while minimizing dose to organs at risk (OARs) [?, ?]. However, practical implementation of a carbon-ion rotational gantry is challenging, with dimensions and weight double those of proton gantries currently limited to institutions in Germany and Japan [3–7]. With advancement of superconducting magnet technology, the first superconducting carbon-ion gantry was installed at the National Institute for Quantum Science and Technology (QST), which reduced the weight from 600 tons at the Heidelberg Ion-Beam Therapy Center (HIT) to 300 tons [?]. Toshiba has increased the superconducting magnetic field strength to 3.50 T to develop a more compact carbon ion gantry. This gantry is currently in the commissioning phase at Yamagata University and Yonsei University Health System, with system size reduced to two-thirds that of the first superconducting gantry at QST [?].

Radiation protection is crucial in carbon-ion radiotherapy due to the necessity for high-energy therapeutic beams when treating deep-seated tumors [9–12]. This importance is amplified when considering rotating gantries for carbon-ion therapy. Given the substantial size and cost of carbon ion rotational gantries, the Shanghai Proton and Heavy Ion Center (SPHIC), like most institutions globally, has not yet adopted this technology [?].

SPHIC currently operates four proton and heavy-ion therapy rooms, catering to diverse tumor locations, depths, and positioning requirements, including three horizontal beamline treatment rooms and one 45° beamline treatment room. Carbon ion radiotherapy, distinguished by its superior physical dosimetry compared to conventional radiation and augmented by the biological advantages of carbon ion beams, holds promise for better preservation of healthy tissue and increased tumor control [?]. Consequently, it has been increasingly employed in treating patients with compromised pulmonary or cardiac function [15–17]. Given the significant correlation between mean lung dose and risk of radiation pneumonitis, minimizing the mean lung dose is imperative [?, ?]. Selection of appropriate beam angles is crucial in achieving this objective [?]. Because particle therapy typically involves fewer beam-entry angles than conventional radiation, providing freedom in beam angle selection is critical from a hardware standpoint.

Usage challenges arise because the fixed-angle beamline and limited roll rotation of the treatment couch hinder optimal treatment for certain patients. Additionally, the 45° beamline treatment room faces significant patient waiting times,

impacting subsequent treatment processes. Recently, a six-degree-of-freedom treatment chair (6DTC) was designed and installed at our center [?, ?]. However, limited by the absence of an upright CT, the 6DTC can only treat patients with head and neck cancers [?, ?]. To address constraints in treating lung and abdominal tumors, a clinical solution has been developed: a rotational pod. This pod enables patients to be fixed and rotated by 360 degrees (180° clockwise and 180° counterclockwise), simulating the effect of a rotational gantry and thereby ensuring necessary beam angles and desired dose distribution.

The concept of treatment pods, pioneered by the Paul Scherrer Institute in Switzerland [?], utilizes pi-meson beams directed at tumors through magnets, allowing three-dimensional movement of patients during treatment. Loma Linda University in the United States employs advanced technology [?], utilizing a white semi-cylindrical pod filled with a liquid polyurethane mixture that expands into solid foam for personalized fixation. In Japan, QST incorporates respiratory gating technology into a rotational pod [?], enabling $\pm 20^\circ$ rotation. The University of Sydney integrates an Elekta linear accelerator and a Patient Rotational System [?] to achieve submillimeter accuracy.

Despite these advances, a paucity of literature provides detailed clinical data on patients treated with pods. This study aims to fill this gap by presenting comprehensive clinical trial data from patients treated with rotational pods at our center. Specifically, this study investigates the dosimetric benefits of increased flexibility in beam angle selection provided by pods for lung cancer patients through pre-dosimetry analysis. Additionally, it validates these dosimetric advantages by examining clinical treatment data from pod patients. The positional accuracy of the pods and the impact of settlement on the stability of tumors and OARs are also calculated and evaluated.

II. Materials and Methods

A. Structure of the Pod

The rotational pod comprises four key components: pod body, pod cover, rotation device, and connectors, as depicted in Figure 1 [Figure 1: see original paper]. Patients can recline inside the rotating treatment pod using a staircase and handrails. The rotating treatment pod can then be transported using a transfer cart and maneuvered into the CT positioning room or treatment room, connecting it with the current clinical 6-DOF robotic arm via connectors. The rotational robotic arm allows for necessary adjustments and displacements of the rotating pod within the treatment space, thereby minimizing collisions with other preexisting equipment in the treatment room. The rotation device enables 360° roll rotation of the pod body and features a locking mechanism. The pod cover facilitates patient entry and closes securely when the patient remains inside. A specifically designed facial opening in the pod cover ensures that the patient's face is fully exposed, fostering improved communication with physicians and therapists upon entering the rotating treatment pod.

B. Pre-Dosimetry Study

Before initiating the clinical trial, a preliminary dosimetry study was conducted to identify suitable indications for pod use. The average lung dose is a critical parameter in lung cancer radiotherapy. Typically, selecting a path that traverses the shortest distance through the lungs can minimize the average lung dose [?]. However, our facility is constrained to beamlines with angles of 90° and 45°, which limits options for beam-entry directions. The application of a pod introduces greater flexibility in entry angle selection.

In this study, 11 patients who demonstrated a reduced path through the lung when the couch was rotated at a certain angle were selected from those who had previously undergone carbon ion radiotherapy at our center. The patients' CT scans and structures were imported into custom-made software and rotated using a rigid transformation method to the angle at which the beam path through the lung was minimized, creating a synthetic CT. The pod simulation plans were optimized using the same prescription and dose limits as those for treatment plans with the conventional treatment couch. Then, target coverage and dose to OARs were compared between the couch-based and pod simulation plans.

C. Immobilization and CT Simulation

During multidisciplinary team (MDT) discussions, physicians and physicists assess whether a patient is potentially suitable for rotational pod treatment based on factors such as tumor location, surrounding normal tissue structures, beam path, and other comprehensive considerations. The treatment angles for the rotational pod are determined based on imaging data. After the MDT discussion, patients undergo immobilization following respiratory training [?, ?]. A low-density foam cradle secures the patient's back, utilizing a thermoplastic mask for fixation when the pod rotation angle is $\leq 30^\circ$ and employing a pod cover with foam filling when the angle exceeds 30° . Following a supine 4DCT scan, the pod is rotated to the treatment angle for another CT scan [?]. The parameters of both CT scans are identical, with slice thickness set to 3 mm. A subsequent scan is performed after 20 minutes at the treatment angle. During this 20-minute interval, the patient remains at the treatment angle, simulating the actual treatment. A respiratory gating system (AZ-733V, Anzai Medical, Japan) was used to mitigate the effects of respiratory motion [?].

D. Treatment Planning

For each patient, two sets of plans were devised: one utilizing supine CT, and the other incorporating CT with a rotated pod. The treatment plan for the supine CT (hereafter referred to as the supine plan) can employ either a 90° or 45° beamline. Given that the key objective of pod development is to alleviate the high occupancy pressure associated with the 45° beamline, the pod plan prioritizes the use of a 90° beamline. Depending on the different stages and

types of tumors in the patients, different prescriptions of carbon ion irradiation were administered. The relative biological effectiveness (RBE) was calculated using local effect model I [?]. The planning objectives aimed to ensure that at least 95% of the internal gross tumor volume (iGTV) and clinical target volume (CTV) received 99% of the prescription dose while minimizing OAR dose with no more than four beams. If the dose to the normal lung exceeds this limit, the target coverage is sacrificed [?]. Owing to the absence of a robust planning technique [?] in Syngo (V13, Siemens, Germany), the planning target volume (PTV) was expanded based on plan-specific factors, such as the chosen beam range uncertainty, ranging from 7–15 mm [?, ?].

Patients deemed to require two pod rotation angles during MDT discussions were immobilized and scanned at both angles. Subsequently, treatment plans were devised separately based on the respective CT scans. Deformable dose accumulation was performed to assess the total dose to the target and OARs using MIM (MIM Software, Cleveland, OH, USA). All plans were reviewed by the chief physician. A comparison was made between the target coverage and OAR doses of the two plan types. Patients were considered eligible for pod treatment based on three criteria: lower OAR dose, comparable target coverage, and no increase in range uncertainty. In cases where both plans demonstrated similar target coverage, OAR doses, and uncertainties, the pod plan was preferred because of its shorter admission waiting time, aligning with the best interests of the patients.

Seven patients were selected to undergo carbon-ion radiotherapy using a pod based on the aforementioned criteria. The characteristics of these seven patients are shown in Table 1 .

E. Alignment and Treatment

The treatment procedure was based on the 6DTC treatment protocol established at our center [?]. During the initial fraction of treatment, an in-room CT scan was conducted to ensure minimal tumor or anatomical changes compared to the planning CT scan at the treatment angle. If the CT results were satisfactory, the pod was repositioned to the first treatment angle using the robotic arms. Repositioning of patients or adaptive planning was initiated when anatomical changes occurred between the review and planning CTs [?]. The position was verified using an image-guided radiation therapy (IGRT) system. A set of orthogonal X-ray images was captured and registered with digitally reconstructed radiographs, focusing on bony anatomy. The positional errors at the initial beam position (PE-B1) were documented, including three translational shifts (lateral, longitudinal, and vertical) and three rotational shifts (iso, pitch, and roll) [?]. Subsequently, the patient's position was adjusted using PE-B1 followed by beam delivery. Upon completion of the first beam delivery, the pod was moved to the second iso rotation angle. The X-ray alignment procedure was repeated to determine the positional errors in the second beam position (PE-B2). After applying PE-B2, a second beam was delivered. This process

was repeated if the treatment fraction involved more than two beams. The attending physician assessed and authorized the alignment before each treatment onsite.

F. Position Accuracy Analysis

In the treatment of lung cancer patients using the pod, maintaining stability in anatomical structures such as the trachea, thoracic vertebrae, and tumor at the treatment angle is paramount, given the inclined position of the body within the pod. This study conducted a comparative analysis of anatomical structural stability based on CT images acquired 20 minutes apart. Physicians delineated key structures, including the iGTV, CTV, trachea, and thoracic vertebrae, in two sets of CT scans obtained around the 20-minute mark. After aligning the two images, changes in anatomical structures were quantitatively assessed using the Dice similarity coefficient (DSC) [?]. The DSC formula is as follows:

$$DSC = \frac{2|A \cap B|}{|A| + |B|}$$

Here, A represents the volume of anatomical structures immediately before, and B represents the volume of anatomical structures 20 minutes later. This approach provides a robust method for evaluating the dynamic stability of anatomical structures during treatment. When $DSC = 1$, this signifies complete overlap between the two structures.

In addition to assessing the settling of patient anatomical structures during the inclined period, the patient's intra-fractional movement and iso-rotational accuracy of pod rotation should also be evaluated. In the alignment process described above, the difference between PE-B1 and PE-B2 represents the entire positioning error involving the pod movement, IGRT system, and patient intrafraction movement [?].

Statistical significance was assessed using a two-tailed paired Student's t-test; $p < 0.05$ was considered statistically significant. The Institutional Review Board reviewed and approved this study.

III. Results

A. Pre-Dosimetry Study

The volumes of the iGTV receiving more than 99% of the prescription dose (V99) were $99.9\% \pm 0.3\%$ (median $\pm$ standard deviation) for the pod plans and $99.9\% \pm 0.8\%$ for the couch plans, with $p = 0.15$ indicating no significant difference. The average dose to the lung-iGTV in the pod plans for the 11 patients decreased by 5–53%, with a p-value less than 0.01 compared to plans using the treatment couch (Figure 2 [Figure 2: see original paper]). Moreover, no significant differences were observed in other OARs, such as the heart, esophagus, spinal cord, and trachea.

B. Planning and Dosimetric Comparison

For all seven patients, both the pod and supine plans had comparable target coverage. The V99 values of the iGTV for the pod plans were $99.8\% \pm 7.4\%$ and $99.9\% \pm 3.7\%$ for the supine plans; $p = 0.31$ indicates no significant difference. The V99 values of the CTV for the pod plans were $98.8\% \pm 8.3\%$ and $99.9\% \pm 8.4\%$ for the supine plans; $p = 0.19$ indicates no significant difference. Except for the mean dose to the lung-iGTV, there were no significant differences in other OARs between the pod and supine plans. Detailed data on targets and OARs are presented in Table 2. The mean dose to the lung-iGTV is shown in Figure 3 [Figure 3: see original paper]. Notably, for patients numbered 3–6, the dose to the lungs was significantly reduced in the pod plan. While the remaining three patients showed no significant difference in lung dose, utilization of the 90° beamline in their cases resulted in a substantial reduction in patient admission waiting time.

C. Patient Alignment

The median treatment duration (from entering to exiting the pod) for the seven patients treated with the pod was 35 minutes (SD 14 minutes) per fraction. The positional errors between beams were recorded and calculated. Figure 4 [Figure 4: see original paper] depicts the deviations in six directions for all seven patients. The median deviations for lateral, longitudinal, vertical, ISO, pitch, and roll directions were $0.0 \text{ mm} \pm 5.3 \text{ mm}$, $-1.2 \text{ mm} \pm 2.3 \text{ mm}$, $-1.1 \text{ mm} \pm 2.7 \text{ mm}$, $0.0^\circ \pm 0.6^\circ$, $-0.1^\circ \pm 0.5^\circ$, and $0.0^\circ \pm 0.8^\circ$, respectively.

For each fraction, the deviation frequencies in the lateral, longitudinal, and vertical directions within 5 mm were 72%, 95%, and 88%, respectively. For deviations within 10 mm, the frequencies were 93%, 100%, and 99% in the three translational directions, respectively. In the ISO, pitch, and roll directions, 91%, 96%, and 87% of deviations were within 1° , respectively. No deviations exceeding 2° were observed for any rotational axes. Notably, these deviations were recorded prior to applying position correction before the second beam delivery, indicating that they did not affect treatment precision.

IV. Position Accuracy Analysis

Six pairs of CT images were acquired. The DSC for the iGTV, CTV, trachea, and thoracic vertebrae based on CT images acquired 20 minutes apart were calculated and recorded. As shown in Figure 5 [Figure 5: see original paper], the tumor target and thoracic vertebrae exhibited high DSC values, indicating good stability of these structures. However, the trachea showed a DSC value of approximately 0.8, suggesting potential settling after 20 minutes of rotation. Nevertheless, a 1–2 mm planning organ-at-risk volume expansion during planning ensures that its dose remains within safe limits.

V. Discussion

This study illustrated the efficacy of the pod in achieving target coverage while minimizing doses to OARs and highlighted the challenges associated with treating lung tumors using a rotational pod. Additionally, we presented patient data from a clinical trial and analyzed positional accuracy and stability of anatomical structures.

The pod's capability to simulate the impact of a rotational gantry provides a pragmatic remedy for institutions lacking access to carbon ion rotational gantries. The study revealed a notable reduction in lung dose in four of the seven patients, suggesting a potential advantage in mitigating radiation exposure to healthy tissues. A lower mean lung dose effectively reduces the risk of radiation pneumonitis [?]. While the remaining three patients did not show dosimetric benefits, the shorter admission waiting time associated with pod plans aligns with patient-centric considerations. A reduced waiting period for admission may additionally attenuate tumor growth during this interval and diminish the likelihood of treatment replanning.

Patient intra-fractional movements and the rotational accuracy of the robotic arm were the main contributors to differences between PE-B1 and PE-B2. Sheng et al. validated the submillimeter mechanical accuracy of a robotic arm in our facility [?]. We observed millimeter-level interbeam movements, with 5–28% of beams experiencing translational shifts exceeding 5 mm. In Lu's study, 46.7% of patients exhibited intra-fractional movements exceeding 3 mm [?]. Zhong et al. reported the presence of 5 mm-level systematic and random errors in lung cancer [?]. These results are consistent with data presented in the current study. This could be attributed to the presence of millimeter-scale motion spaces in patients, even when thermoplastic masks are in place. Additionally, patient respiratory and cardiac motions contributed to this error. However, Figure 4 indicates that the error follows a Gaussian distribution, with 72%–95% of data in the three translational directions falling within 5 mm. Although individual fractions exceeding 5 mm can lead to underdosing of the target or overdosing of OARs, segmentation into 10–22 fractions can reduce the impact of single-fraction errors to some extent. This millimeter-level interbeam movement suggests the possibility of relative displacement between the patient, pod, and foam. However, because the pod is designed to be uniform in water equivalence at all angles and depths, and the foam is a low-density material, this error theoretically has minimal impact on dosimetry. Kanai et al. examined the dosimetric effects of displacement between the patient and treatment couch when a carbon-ion beam passed through the couch using a rotating gantry. For patients with lung cancer, an average displacement of 4.2 mm was observed; however, dosimetric analysis indicated no significant impact on target coverage and V20 of the ipsilateral lung [?]. Based on these potential effects, a 7–15 mm margin was expanded to generate the PTV during treatment planning.

Position verification at each iso rotation angle is strongly recommended to elim-

inate error and ensure accuracy. The time required for pod treatment is $35 \text{ min} \pm 14 \text{ min}$ per fraction. Moreover, patients with lung cancer require $21.5 \text{ min} \pm 4 \text{ min}$. As described earlier, the difference between PE-B1 and PE-B2 can sometimes exceed 5 mm, which necessitates position verification before each beam irradiation. This additional step extends treatment time. However, from the perspective of beamline efficiency, this has minimal impact because our facility is equipped with four treatment rooms. During position verification, the beamline can be allocated to other rooms, and treatment can proceed once position correction is completed. Therefore, there was no significant difference in beam time between pod patients and those using the treatment couch.

To the best of our knowledge, there is a lack of clinical data on the settling effects of organs when patients shift from upright to lying down or tilted positions. Importantly, this settling phenomenon is not confined to patients undergoing pod treatment; individuals in supine or prone positions, transitioning from standing to lying-down posture, may also experience potential settling of internal body structures. In this study, DSC was used to evaluate the settling of tumors, trachea, and vertebrae 20 minutes after patients underwent a specific rotational angle. The DSC of these structures, excluding the trachea, were found to be greater than 0.85, which is considered an appropriate threshold for automatic image segmentation [?].

The pod, as a gantry-free solution, can provide more freedom in beam-angle selection when used with a fixed ion beamline compared to the fixed beamline itself. Although it can simulate a 360° beam angle, patient stability may be a concern. While its impact is small, the use of a rotating gantry eliminates the issue of patient stability. We acknowledge this as a disadvantage compared to the gantry. Nevertheless, its low cost makes it a viable option for low- and middle-income countries. The recent trend in upright radiotherapy, facilitated by chairs that can rotate 360° , provides an alternative to rotational gantries [?, ?, ?]. However, this approach is only suitable for treating patients with head and neck lesions in the absence of an upright CT [?]. One notable advantage of the pod is that it eliminates the need for an additional upright CT, distinguishing it from limitations associated with the current trend of upright radiotherapy.

This study has certain limitations, such as a relatively small sample size. However, in the developmental phase of an innovation, studies with small sample sizes can play a pivotal role, and further investigation is required on this topic. Additionally, owing to the lack of real-time KV imaging guidance, it was not possible to obtain patient movement data within individual treatment fields for analysis and mitigation of patient motion. Further research and technological advancements are required to refine and expand the clinical applications of rotating pods in radiation therapy.

VI. Conclusion

Preliminary clinical application of the rotational pod for lung tumors in fixed-ion beam lines presents promising results. This study provides clinical data on the dosimetric considerations, treatment efficiency, and anatomical structural stability associated with rotational pod treatment. However, as an innovative solution to the challenges of ion-beam therapy, the rotating pod at SPHIC warrants further exploration and refinement. Future developments could focus on enhancing patient comfort by introducing 3D printing into patient immobilization procedures and establishing robust simulation systems with 4D optimization to further refine treatment plans. Continued research and clinical trials, including those expanding indications for breast cancer and other malignancies, are essential for validating and optimizing the efficacy of this novel approach.

Acknowledgments

The authors appreciate Michael F. Moyers from the Shanghai Proton and Heavy Ion Center for designing the rotational pods.

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