Positioning Reproducibility in Upright Image-Guided Proton Therapy for Head and Neck Cancer Patients

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Abstract

Background and purpose: *To evaluate the reproducibility of patient positioning during upright treatment with image-guided adaptive proton therapy (IGAPT) for head and neck cancer.* ***Materials and methods:*** *10 head and neck patients were treated with gantry-less IGAPT, which includes daily 3D computed tomography (CT) and two 2D kilovoltage (kV) radiographs before treatment and additional weekly 3D CT immediately after irradiation. All procedures were performed in the carbon chair on the 6 degrees of freedom (DoF) robotic positioner.* ***Results:*** *We registered shifts in patient positioning using 3D/3D registration prior to treatment at the imaging isocenter: X = -0.1±3.9 (mean ± STD) mm, Y = -3.7±3.5 mm, Z = 0.5±6.2 mm, these corrections were applied after the patient was moved to the treatment isocenter and the following shift was obtained there using 2.5D registration: X = -0.31±1.37 mm, Y = -0.02±1.33 mm, Z = 0.59±1.55 mm. Finally, the weekly follow-up 3D/3D registration shows X = -0.2±1.2 mm, Y = -0.0±1.4 mm, Z = 2.3±2.0 mm.* ***Conclusion:*** *A novel image-guided gantry-less proton therapy shows reliable results in terms of patient positioning for head and neck cases during clinical trials. This fact confirms the suitability of gantry-less PT for head and neck treatment.*

Introduction

Image-Guided Adaptive Proton Therapy (IGAPT) is an advanced form of proton therapy (PT) used in radiation oncology to treat cancer. It combines the precision of PT with an adaptation of treatment plans based on changes in tumor size, shape, as well as patient positioning during treatment [1]. Due to the Bragg peak, PT can deliver a highly conformal dose to a target; however, the Bragg peak must be correctly placed in the target to utilize the potential of proton beams. Compared to photons, protons have additional uncertainties in the range, or penetration, of the beam in tissue [2]; these uncertainties are predominately influenced by the densities of tissue through which the beam passes. Image guidance (along with proper immobilization) minimizes these uncertainties and illustrates the greater importance it has on PT compared to photon therapy [3].

A key limiting factor in the spread of proton therapy is the initial price of the PT center, which is largely determined by the proton beam rotating system – gantry [4]. One option to significantly reduce the cost and size of PT centers is the use of a fixed horizontal beam line with a rotating chair system for patient positioning [5], [6] with treatment performed in a mostly upright position [7], [8]. Thus, recent work shows the reasonableness of using upright patient positioning systems for PT of the head and neck [9], [10]. The standard practice in PT today is to use 3D computed tomography (CT) in the supine position for radiation planning. However, there are concerns that the patient's anatomy may change significantly from the supine to upright position, especially for the thorax, abdomen and pelvic regions [11], [12]. This should be considered when positioning the patient upright, and when using horizontal CT, additional anatomy recording in the treatment position should be performed [6].

In this paper, we investigated a novel IGAPT system that combines upright treatment and imaging in the same room. We used daily 3D/3D CT registration in the imaging isocenter, complemented by orthogonal X-ray based 2D/3D registration in the treatment isocenter. Following the work [13], [14] on the reproducibility of patient positioning in upright treatment, we evaluated the results of the first 10 head and neck patients treated with a fully image-guided workflow in upright gantry-less proton therapy.

Material and Methods

A novel proton therapy facility presented in the current work combines a proton synchrotron, a gantry-less beam delivery system with an upright patient positioning and immobilization unit, as schematically shown in Figure 1.

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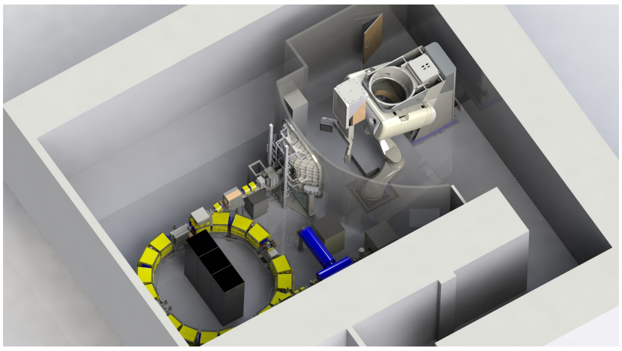

Figure 1: *P-Cure proton therapy facility in Shilat, Israel, combines compact accelerator and upright patient positioning system in a single room.*

Patient Positioning and Imaging

The PAtient Robotic posiTioning and Imaging System (P-ARTIS) consists of a patient positioning system (PPS) with a convertible patient chair, a vertical 4DCT imaging system, and an orthogonal 2D X-ray imaging system. The P-ARTIS PPS kinematics are based on the Leoni Orion, a six-degrees-of-freedom (DoF) robotic system approved for particle therapy applications. The translational motion of the robot is determined by three axes: two orthogonal axes (X, Y) and a Z-axis set parallel to the beam trajectory. The maximum lateral travel is 4,880 m, vertical - 1,184 m and longitudinal - 2,230 m 1. Its geometry includes articulated surfaces: base, elbow, and wrist. The elbow/base allows $\pm$ 25° of left and right rotation, while the wrist offers ±100° of rotation, allowing full 360° access to the treatment volume via the elbow/base joint. The PPS is calibrated for various loads up to 240 kg with an accuracy of ±0.5 mm (95% confidence) and has the capacity to scale the weight up to 360 kg.

The P-ARTIS CT utilizes a Phillips Brilliance Big Bore platform angled at 20° relative to the vertical axis of the room. Patient motion during image acquisition is managed by a sliding platform on the CT base, using the same control interface as the traditional moving couch. The 2D X-ray system provides planar, orthogonal radiographic imaging of patient geometry at the treatment isocenter position. It is designed with two 150 kV X-ray sources positioned on either side of the nozzle of the proton beam delivery system and ceiling-mounted retractable 30 cm × 30 cm flat PaxScan 3030DX detectors (Varian Medical Systems, USA).

System was calibrated every day prior treatment. The paper includes the data from April 2023 to January 2024, or 196 treatment shifts. A pass criterion for daily QA of 3D/3D registration was set as 1 mm and 1 degree.

Figure 2: *A patient immobilized in a seated position during acquisition of 2 orthogonal 2D X-ray images.*

Patient Immobilization

The patients have been immobilized with the 5-point thermoplastic masks (Orfit Ltd) fixed on chair backrest according to the standard procedure. In most of the cases the mask prepared prior to the treatment served for the entire course. In a few cases, in which the adaptive plan was generated along the session, the new masks have been prepared accordingly.

Patient Cohorts

The first 10 patient data treated with proton therapy at the Sharett Institute of Oncology of Hadassah Medical Center in 2023. 7 patients had 35 fractions, 1 – 33, 1 – 30 and 1 – 18. In total 326 irradiation sessions were performed.

Results

Calibration IGRT

Mean registration of 0.34 mm and 0.21 mm was found for 3D/3D and 2.5D/3D registration as shown in Figure 3, which confirmed the reliability of the system during operation.

Interfraction Positioning Reproducibility

Interfraction positioning reproducibility was defined as the 3D/3D registration vector calculated to bring the patient to the isocenter position demonstrated by the first row in Figure 4 and Figure 5.

Three hundred and eighteen data points were calculated. Both translation and rotation parameters were calculated. -0.1 $\pm$ 3.9 mm, -3.7 $\pm$ 3.5 mm, 0.5 $\pm$ 6.2 mm are the mean values calculated along the x, y, and z axes, respectively; while -0.6 $\pm$ 1.8 deg, -0.3 $\pm$ 1.4 deg, -0.30 $\pm$ 1.5 deg are the mean values calculated as rotation values around the x, y, and z axes, respectively.

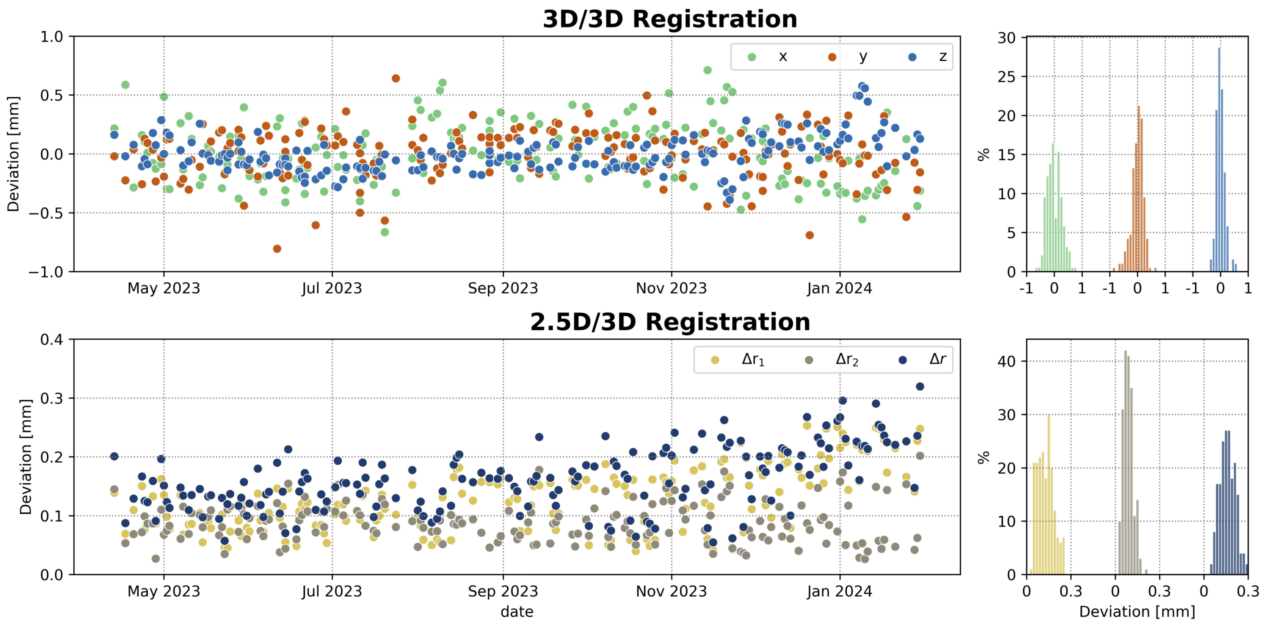

Figure 3: *Imaging system calibration results over 10 months.*

Table 1: *Patient data*

N	Diagnosis	N, 3D/3D	N, 2.5D/3D	N, follow up
1	Buccal Mucosa	26	72	3
2	Buccal Mucosa	36	105	5
3	Maxillary sinus Carcinoma	33	67	6
4	Larynx Squamous Cell Carcinoma	36	72	5
5	Tongue Cancer	31	62	7
6	Salivary Gland Carcinoma	34	70	6
7	Hypopharyngeal Cancer	18	54	2
8	Oropharyngeal Squamous Cell Carcinoma with Bilateral Adenopathy	36	108	6
9	Hypopharyngeal Cancer	36	108	7
10	Tongue Cancer	32	60	8

Intrafraction Positioning Repeatability

Intrafraction positioning reproducibility was defined as a 2D/3D registration vector that was computed to correct the patient position per each field.

Seven hundred thirty-nine data entry points have been calculated (Fig. 2, B). Both translation and rotation parameters were computed. -0.31 $\pm$ 1.37 mm, -0.02 $\pm$ 1.33 mm, 0.59 $\pm$ 1.55 mm are the mean values computed along x, y, and z axes respectively; while -0.09 $\pm$ 0.89 deg, -0.01 $\pm$ 0.66 deg, -0.04 $\pm$ 0.72 deg represent the mean values computed as rotational values about x, y, and z axes, as shown by the second row in Figure 4 and Figure 5.

Positioning Intrafraction Rigidity

Intrafraction positional stiffness was defined as a 3D/3D registration vector calculated from a 3D data set acquired at the beginning of the fraction and at its end before the patient was released from immobilization.

Data were acquired weekly and totaled 55 data acquisition points (Fig. 2, B). Both translational and rotational parameters were calculated. -0.2 $\pm$ 1.2 mm, -0.0 $\pm$ 1.4 mm, 2.3 $\pm$ 2.0 mm are the mean values calculated along the x, y, and z axes, respectively; while -0.4 $\pm$ 0.8 deg, 0.0 $\pm$ 0.6 deg, -0.1 $\pm$ 0.7 deg are the mean values calculated as rotation values around the x, y, and z axes, respectively. Follow-up results are demonstrated by the third row in Figure 4 and Figure 5.

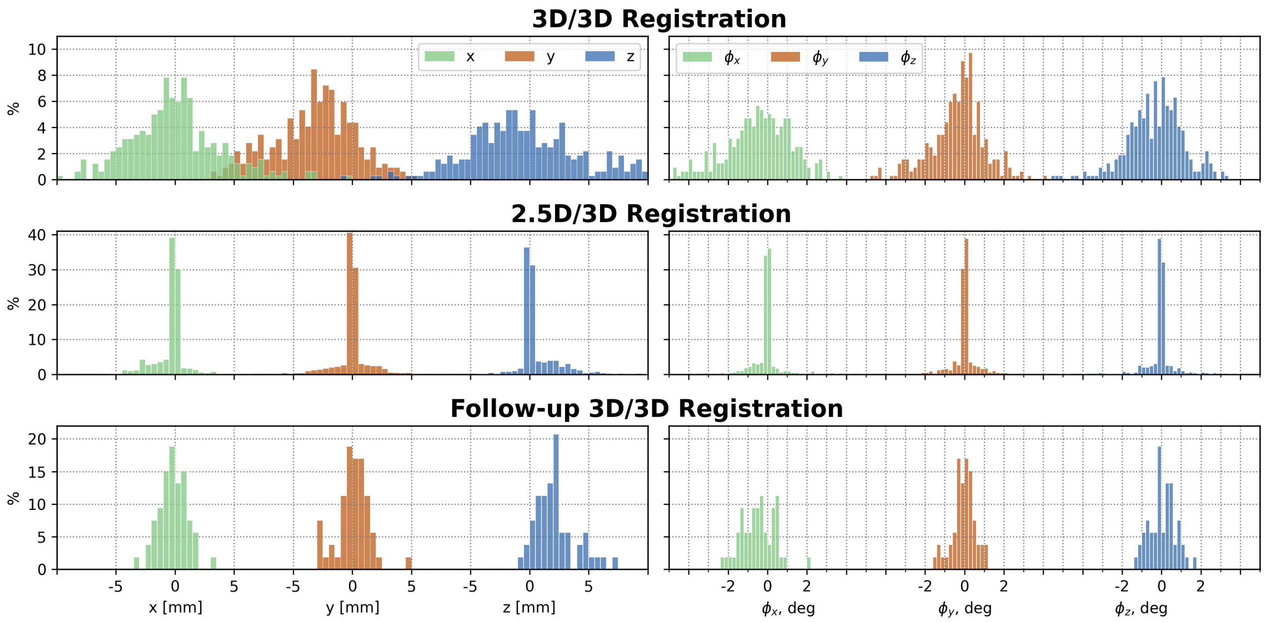

Figure 4: *Distribution of registered shifts for all modalities.*

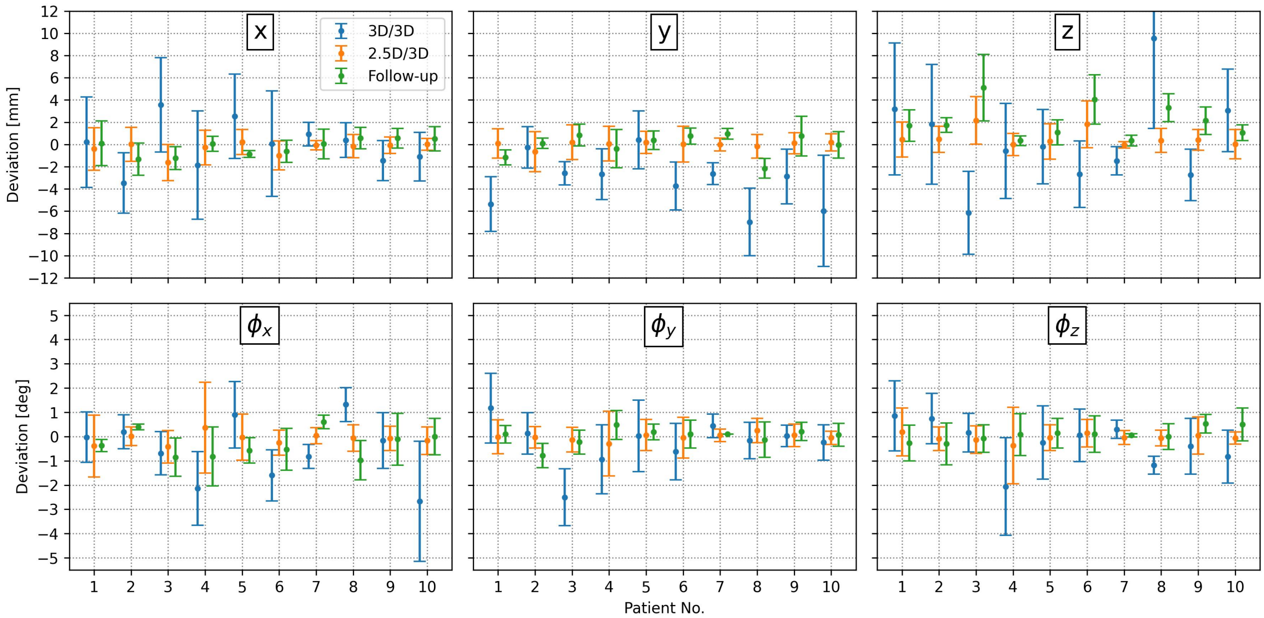

Figure 5: *Mean ± STD of registered shifts for all modalities and patients listed in Table 1.*

Discussion

Treatment of patients in a seated position attracts a practical interest of institutions considering establishment of proton therapy offering at their premises. Treating patients in a seated position opens up the possibility of delivering treatments without large, bulky and expensive gantries, saving significant setup and operating costs of such an endeavor. The commercial opportunity became apparent in 2016, when the first commercial vertical CT system was installed and used for clinical purposes at the Northwestern Medicine Proton Center in Chicago (Figure 6). The installation allowed the center to simulate and treat in a seated position. Since then, more than 500 patients have been treated, demonstrating the feasibility and clinical benefits of treating patients in a seated position, including increased lung volume and reduced motion of organs in the chest [11].

To further support the idea of gantry-less (seated treatments) delivery of proton therapy, we monitored positioning parameters during actual treatment of cancer patients with malignancies in the head and neck anatomy. Specifically, we addressed: (1) in-

Figure 6: *The first P-ARTIS was installed at the Northwestern Medicine Proton Center in Chicago.*

terfractional positioning accuracy as a function of position registration at setup, (2) intrafractional positioning accuracy per treatment field, and (3) intrafractional patient position rigidity monitored by registering the shift in patient position over the entire length of the fraction.

Mean interfraction values ranged from -3.7 to 0.5 mm and -0.6° to -0.3°. Considering that the system is fully integrated and does not use lasers for initial positioning, the values shown are more than satisfactory.

The mean intrafraction values ranged from -0.31 to 0.59 mm and -0.09° to -0.01°, representing the stereotactic level accuracy of the displacements. These values are particularly important because they directly demonstrate the feasibility of proper immobilization during treatment.

Both inter- and intra-fraction accuracy parameters show high positioning accuracy, which supports the idea of treating patients in a sitting position. To verify the overall positioning rigidity, once a week (when possible) we acquired a CT dataset after treatment, just before patients were released from immobilization. During 30 minutes of immobilization, patients remain stable overall. However, analysis of the patient's position along the vertical axis revealed slight systematic downward shifts, indicating that the patient is prone to sagging by up to 2 mm on average.

To verify the applicability of this finding to patient immobilization during treatment, further analysis of patient position immediately after treatment using kV/kV image registration will be addressed in the future.

Conclusion

Here, we demonstrated for the first time the positioning accuracy of head and neck cancer patients treated in a seated position for the entire workflow, including patient immobilization accuracy, positioning accuracy for each irradiation field, and follow-up imaging at the end of multiple fractions for the first 10 patients. The results clearly demonstrate the feasibility of such a setup and support the idea of treating patients with a compact, gantry-less proton therapy solution.

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