Physica Medica 63 (2019) 19–24

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

The impact of the offset distance between the planning target volume and isocenter on irradiation time in TomoTherapy: A phantom study

Makoto Hirata[a,b], Kohei Hanaoka[a,c], Kenji Matsumoto[a,c], Mikoto Tamura[a,c], Masahiko Okumura[c], Hajime Monzen[a,*]

[a] Department of Medical Physics, Graduate School of Medical Sciences, Kindai University, 377-2, Ohno-Higashi, Osakasayama, Osaka 589-8511, Japan
[b] Department of Radiology, Otsu Red Cross Hospital, 1-1-35, Nagara, Otsu, Shiga 520-8511 Japan
[c] Department of Central Radiology, Kindai University Hospital, 377-2, Ohno-Higashi, Osakasayama, Osaka 589-8511 Japan

ARTICLE INFO

Keywords:
Offset
Lok-bar
TomoTherapy
Irradiation time

ABSTRACT

Purpose: The influence of the offset distance from treatment target to gantry isocenter (GIC) on the dosimetric parameter and irradiation time was investigated using TomoTherapy

Methods: The reference position was defined as the centers of both the I'mRT phantom and planning target volume (PTV) with a spherical of 4 cm diameter aligned with the GIC. The dose calculations were performed in two offset methods with 2 and 12 Gy/fr, Method 1. The PTV was moved from 0.0 to 12.5 cm along the RL direction and −5.0 to 5.0 cm along the AP direction (PTV offset), Method 2. The phantom was moved from 0.0 to −7.5 cm along the RL direction and −5.0 to 5.0 cm along the AP direction (Phantom offset). The maximum, minimum and mean doses, homogeneity index, conformity index, irradiation time, and monitor unit were compared.

Results: The irradiation times increased with increasing PTV offset. The increases in the irradiation time were 54.4% and 40.8% at PTV offsets of 12.5 cm along the RL direction for 2 and 12 Gy/fr, while the increases were 20.1% and 15.0% at a PTV offset of 5.0 cm along the AP direction. An increased irradiation time was not observed for the phantom offset. The offset didn't affect the other parameters.

Conclusions: The PTV location offset of ≥5 cm from the GIC along the RL and AP axes increased the irradiation time; therefore, the PTV should be aligned with the GIC as much as possible to reduce the irradiation time on TomoTherapy.

1. Introduction

Various treatments can be performed using TomoTherapy (Accuray Inc., Madison, WI, USA) owing to its unique binary collimator and flattening filter free (FFF) beam. The helical irradiation enables irradiation fields exceeding 100 cm in the cranio-caudal direction of the patient's body axis, although removal of the flattening filter causes a low offset-axis dose rate compared with the center-axis dose rate [1–3].

In a general linear accelerator (Linac), offsetting the treatment couch enables target irradiation along the right-left (RL) axis. However, in TomoTherapy, the treatment couch's movement is restricted to only ± 2.5 cm along the RL axis of the patient's body [4]. It is difficult for a target that is offset along the RL axis to be position closer to the gantry isocenter (GIC), which receives the highest irradiation dose, resulting in a lower irradiation dose rate for such targets and thus inefficient irradiation conditions.

Xu et al. reported the benefit of patient shifting depending on the shape of the planning target volume (PTV) and its spatial relationship with the patient's central axis; shifting the patient's position is recommended for cases in which the PTVs are away from the patient's central axis [5]. Monzen et al. described that higher precision is required to ensure the accuracy of irradiation positioning, repeatability of patient position and patient fixation precision to control body movement during radiation therapy [6]. The American Association of Physicists in Medicine task group report 176 recommends the use of a couch and various fixtures typically constructed from carbon-fiber-reinforced plastic because of its high mechanical strength, low specific density, and relative radiotranslucence [7]. There are reports on the importance of offset and accuracy of high precision radiotherapy using a patient immobilization device. The purpose of this study was to

* Corresponding author at: Department of Medical Physics, Graduate School of Medical Sciences, Kindai University, 377-2, Onohigashi, Osakasayama, Osaka 859-8511, Japan.
E-mail address: hmon@med.kindai.ac.jp (H. Monzen).

https://doi.org/10.1016/j.ejmp.2019.05.009
Received 25 November 2018; Received in revised form 19 April 2019; Accepted 18 May 2019
Available online 25 May 2019

Fig. 1. The HM-bar. The top image shows the entire HM-bar, and the bottom image shows an enlarged view of the offset adjustment hole. All if the constructions are made of radiation-absorbing material, and it is easy to change the offset by adjusting the knob position.

investigate the impact of target and patient offsetting on the TomoTherapy dosimetric parameter and irradiation time along RL and anterior-posterior (AP) axes with a newly developed index bar [6,8] that enables a fixed offset of the patient's position along the RL axis.

2. Methods

2.1. Materials

The influence of the distance between the GIC and PTV on the dosimetric parameter and irradiation time were investigated. The treatment plans were created by offsetting only the PTV to the left side and AP of the patient's body axis with the TPS, and the dosimetric parameters and irradiation times with and without offset were compared. An I'mRT phantom (IBA Dosimetry GmbH, Schwarzenbruck, Germany) was set on a computed tomography (CT) couch with an HM-bar (Nichigen Co. Ltd, Tokyo, Japan) and HIP-FIX (CIVCO Medical Solutions, Kalona, IA, USA). The HM-bar is shown in Fig. 1. There are holes in the body of the HM-bar that can be used to adjust the position of the knob that fixes the patient immobilization device to the couch and can move the fixture 7.5 cm at 2.5 cm intervals. The main frame of the HM-bar is made of carbon fiber-reinforced plastic board, and the pin part is made of polyacetal resin blocks [6,8], which are acceptable in the clinical setting for improvement of the dose delivery accuracy. The low attenuation and use of the HM-bar could minimize the problems that affect dose calculation, accuracy of the target contour, and precision of image registration without artifacts [8].

2.2. Planning criteria

In this study, intensity-modulated radiotherapy (IMRT) plans were created by two prescribed dose types. First, the prescribed dose was 50 Gy/25 fr to 95% of the PTV volume, and the plan's maximum dose to the PTV was ≤ 55 Gy. The machine parameters were as follows: field width of 2.5 cm, pitch of 0.43, and modulation factor (MF) of 1.6. In the other type, the prescribed dose was 48 Gy/4 fr to 95% of the PTV volume [9], and the plan's maximum dose to the PTV was ≤52 Gy. The machine parameters of all treatment plans were as follows; field width of 2.5 cm, pitch of 0.143, and MF of 1.6.

2.3. Method 1: influence of planning target volume offset along the RL and AP directions on the dosimetric parameter and irradiation time

The I'mRT phantom was set on the center of the treatment couch and scanned with a 16-row CT (Toshiba Aquilion LB, Toshiba Medical Systems Co., Tochigi, Japan) for treatment planning (Planning Station, 5.0.5.18 19-Nov-2014: Accuray Inc., Madison, Wis., USA). The center of the PTV, a spherical target volume of 4 cm diameter, was aligned with the GIC and phantom center to establish an offset of 0 cm (i.e. the reference position), as shown in Fig. 2a.

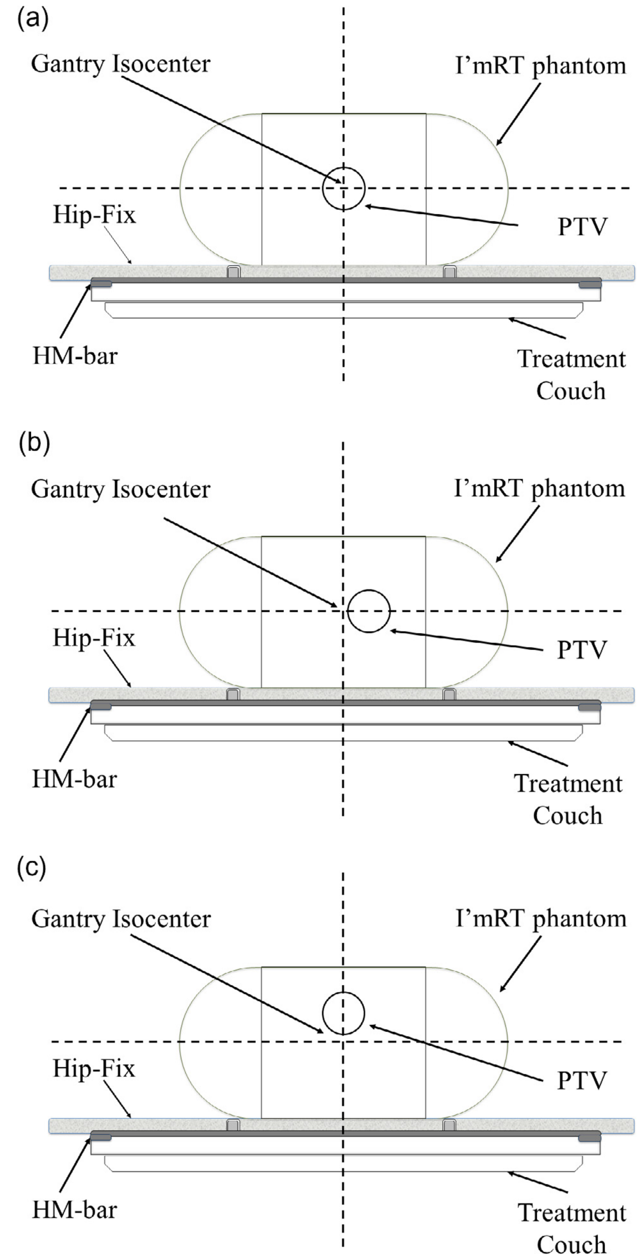

Fig. 2. (a) Schematic of the geometry for PTV offset. The reference position of phantom and PTV. We installed an I'mRT phantom using an HM-bar and HIP-FIX on a CT couch. The phantom center was aligned to coincide with the GIC (dotted line), and then the PTV center was set as the reference offset (0 cm), and the PTV was a spherical target volume with a diameter of 4 cm. (b) Schematic of the geometry for PTV offset. The PTV center position was moved 2.5 cm to the left side of the patient's body axis. (c) Schematic of the geometry for PTV offset. The PTV center position was moved 2.5 cm to the anterior side of the patient's body axis.

The PTV center positions were then moved 2.5, 5.0, 7.5, 10.0, and 12.5 cm to the left of the phantom's center axis, and IMRT treatment planning was performed with the same dose constraints as those of the reference position for each PTV position. Fig. 2b shows a position where the PTV was moved 2.5 cm along the RL axis direction (i.e., PTV offset RL 2.5 cm). In addition, we investigated the influence of the PTV offset along the AP direction of the patient's body axis on dosimetric parameter and irradiation time. The PTV positions were moved −5.0, −2.5, 2.5, and 5.0 cm to the AP direction of the patient's body axis, and

IMRT treatment planning was performed with the same dose constraints as those of the reference position for each PTV position. Fig. 2c shows a position where the PTV was moved 2.5 cm in the anterior direction (PTV offset AP 2.5 cm). The differences in irradiation time between each PTV offset and without condition were calculated with Eq. (1):

$$\text{Difference}(\%) = \frac{(\textit{Irradiation Time with each PTV offset} - \textit{Irradiation Time for reference position})}{\textit{Irradiation Time for reference position}} \times 100 \quad (1)$$

The following evaluation criteria for dosimetric parameter and irradiation time were calculated [10]: maximum dose, minimum dose, mean dose, irradiation time, monitor unit (MU), homogeneity index (HI), and conformity index (CI) [11]. The HI and CI were calculated with Eqs. (2) and (3) as follows:

$$\text{HI} = \frac{(PTV_{2\%} - PTV_{98\%})}{\textit{prescribed dose}} \quad (2)$$

$$\text{CI} = \frac{(V_{100\%})}{\textit{Volume of PTV}} \quad (3)$$

where $PTV_{2\%}$ is the dose received by 2% of the PTV, $PTV_{98\%}$ is the dose received by 98% of the PTV in Eq. (1), and $V_{100\%}$ is the volume of the target receiving the prescribed dose in Eq. (2). The irradiation time obtained from each IMRT treatment plan was compared with the irradiation time for the reference position. The difference of irradiation time for each plan was calculated by Eq. (1).

2.4. Method 2: influence of the phantom offset along the RL and AP directions on dosimetric parameter and irradiation time

In Method 2, we investigated the influence of the phantom offset on dosimetric parameter and irradiation time. The I'mRT phantom, which was moved −2.5, −5.0, and −7.5 cm to the right of the patient's body axis with an HM-bar and HIP-FIX, was scanned with a 16-row CT. During each treatment planning, the center of the PTV, which had a spherical target volume 4 cm in diameter, was aligned with the GIC as shown in Fig. 3a (i.e. phantom offset RL −2.5 cm), and the treatment plans had the same constraints as in Method 1. Parameters that provide information regarding the dosimetric parameter, such as maximum dose, minimum dose, mean dose, MUs, HI, CI, and irradiation time, were compared between the I'mRT phantom offsets and the reference position.

In addition, we investigated the influence of the phantom offset along the AP direction of the patient's body axis on dosimetric parameter and irradiation time. The I'mRT phantom, which moved −5.0, −2.5, 2.5, and 5.0 cm to the AP direction of the patient's body axis, was planned with TPS. During each treatment planning, the center of the PTV, which had a spherical 4 cm diameter target volume, was aligned with the GIC as shown in Fig. 3b (i.e. phantom offset AP −2.5 cm). Treatment plans were created using the same constraints as in Method 1.

In this article, the offset patterns of Method 1 and 2 are denoted as the 'PTV offset' and 'phantom offset', respectively.

2.5. Impact of PTV offset vs. phantom offset on irradiation time

Using the results of Method 1 and 2, the irradiation times were compared between PTV offsets of 2.5, 5.0, and 7.5 cm and phantom offsets of −2.5, −5.0, and −7.5 cm with the same PTV position in the phantom along the RL direction. In the AP direction, the irradiation times were compared between PTV offsets of −5.0, −2.5, 2.5, and 5.0 cm and phantom offsets of −5.0, −2.5, 2.5, and 5.0 cm with the same PTV position in the phantom, respectively. The differences in irradiation time between the PTV offset and phantom offset conditions were calculated using Eq. (4).

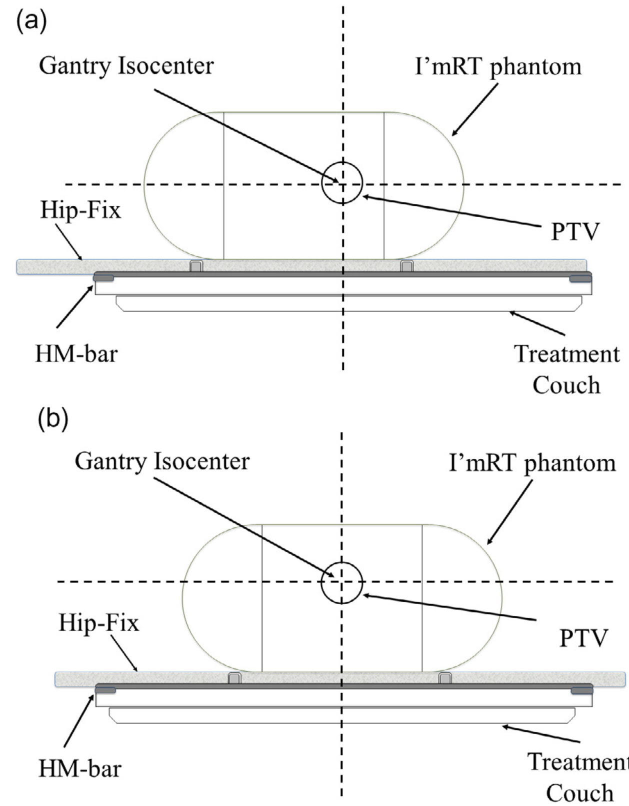

Fig. 3. (a) Schematic of the geometry for phantom offset. Phantom was moved −2.5 cm along the RL direction, in which CT imaging was performed after the phantom position was moved 2.5 cm in the same direction and with the same magnitude of offset as the PTV offset of 2.5 cm (Fig. 2b). (b) Schematic of the geometry for phantom offset. Phantom was moved −2.5 cm along the AP direction, in which CT imaging was performed after the phantom position was moved 2.5 cm with the couch in the same direction and with the same magnitude of offset as the PTV offset of 2.5 cm (Fig. 2c).

$$\text{Difference}(\%) = \frac{\textit{Irradiation Time with PTV offset value} - \textit{Irradiation Time with phantom offset value}}{\textit{Irradiation Time with phantom offset value}} \times 100 \quad (4)$$

The maximum dose, minimum dose, mean dose, irradiation time, MUs, HI, and CI between the PTV offset group (Method 1) and the phantom offset group (Method 2) were compared when the PTV was the same position in the phantom with the nonparametric Wilcoxon signed-rank test [5]. Statistical analyses were performed with EZR on R Commander, version 3.3.2 (Saitama Medical Center, Jichi Medical University, Saitama, Japan) [12] and $p < 0.05$ was considered statistically significant.

3. Results

3.1. Method 1. Influence of the planning target volume offset along the RL and AP directions on the dosimetric parameter and irradiation time

The influence of the PTV offset along the RL direction on dosimetric parameter and irradiation time is shown in Table 1. The dosimetric parameter was not affected by the PTV offset, except for the minimum dose with a PTV offset distance of 12.5 cm. The irradiation times and

Table 1
Influence of the PTV offset along the RL direction on irradiation conditions.

(a) Prescribed dose of 50 Gy/25 fr (2 Gy/fr)

PTV offset RL (cm)	0.0	2.5	5.0	7.5	10.0	12.5
Max dose (Gy)	52.32	52.13	51.91	51.96	52.26	52.57
Min dose (Gy)	48.19	49.12	49.74	49.93	49.19	45.63
Mean dose (Gy)	51.37	51.41	51.16	51.20	50.89	50.84
Time (s)	82.4	83.8	90.0	96.3	117.6	127.2
Difference of Irradiation time (%)	–	1.7	9.2	16.9	42.7	54.4
MU	1048	1068	1159	1249	1559	1698
Difference of MU (%)	–	1.9	10.6	19.2	48.8	62.0
HI	0.04	0.03	0.03	0.03	0.04	0.05
CI	0.99	1.00	1.00	1.00	0.96	0.99

(b) Prescribed dose of 48 Gy/4 fr (12 Gy/fr)

PTV offset RL (cm)	0.0	2.5	5.0	7.5	10.0	12.5
Max dose (Gy)	49.88	50.04	49.6	49.58	49.76	50.13
Min dose (Gy)	45.9	47	47.42	47.56	46.6	43.69
Mean dose (Gy)	49.11	49.38	49.06	48.98	48.73	48.82
Time (s)	444.1	436.7	472.3	509.2	617.5	625.3
Difference of Irradiation time (%)	–	−1.7	6.3	14.7	39.0	40.8
MU	6290	6186	6698	7237	8806	8917
Difference of MU (%)	–	−1.7	6.5	15.1	40.0	41.8
HI	0.04	0.04	0.03	0.03	0.03	0.04
CI	0.98	0.99	0.98	0.99	0.98	0.98

MUs increased up to 54.4% and 62.0%, respectively, with PTV offset distances increasing with the prescribe dose of 2 Gy/fr. Alternatively, the irradiation times and MUs increased up to 39.0% and 40.8%, respectively, with PTV offset distances increasing with the prescribed dose of 12 Gy/fr.

The influence of the PTV offset along the AP direction on the dosimetric parameter and irradiation time is shown in Table 2. The dosimetric parameter was not affected by the PTV offset. The irradiation times and MUs increased up to 20.1% and 22.8%, respectively, with the PTV offset distance increasing with a prescribe dose of 2 Gy/fr. Alternatively, the irradiation times and MUs increased up to 15.0% and 15.3% with the PTV offset distance increasing with prescribe dose of 12 Gy/fr.

Table 2
Influence of the PTV offset along the AP direction on irradiation conditions.

(a) Prescribed dose of 50 Gy/25 fr (2 Gy/fr)

PTV offset AP (cm)	−5.0	−2.5	0.0	2.5	5.0
Max dose (Gy)	51.94	51.86	52.32	52.04	52.12
Min dose (Gy)	49.91	48.16	48.19	49.64	49.64
Mean dose (Gy)	50.90	50.92	51.37	51.24	50.84
Time (s)	99.0	82.6	82.4	84.5	97.5
Difference of Irradiation time (%)	20.1	0.2	–	2.5	18.3
MUs	1287	1052	1048	1078	1266
Difference of MUs (%)	22.8	0.4	–	2.9	20.8
HI	0.03	0.03	0.04	0.03	0.04
CI	0.99	0.98	0.99	1.00	0.99

(b) Prescribed dose of 48 Gy/4 fr (12 Gy/fr)

PTV offset AP (cm)	−5.0	−2.5	0.0	2.5	5.0
Max dose (Gy)	49.47	49.4	49.88	49.81	49.63
Min dose (Gy)	47.45	45.39	45.9	47.6	47.61
Mean dose (Gy)	48.52	48.38	49.11	49.2	48.56
Time (s)	507.4	473.6	444.1	447.5	510.5
Difference of Irradiation time (%)	14.3	6.6	–	0.8	15.0
MUs	7212	6716	6290	6337	7255
Difference of MUs (%)	14.7	6.8	–	0.7	15.3
HI	0.03	0.03	0.04	0.03	0.03
CI	0.96	0.94	0.99	0.94	0.95

Table 3
Effect of phantom offset along the RL direction on irradiation conditions.

(a) Prescribed dose of 50 Gy/25 fr (2 Gy/fr)

Phantom offset RL (cm)	0.0	−2.5	−5.0	−7.5
Max dose (Gy)	52.32	52.20	51.81	52.09
Min dose (Gy)	48.19	49.87	48.68	49.93
Mean dose (Gy)	51.37	51.42	51.08	51.08
Time (s)	82.4	84.3	81.3	84.1
Difference of Irradiation time (%)	–	2.3	−1.3	2.1
MUs	1048	1077	1032	1074
Difference of MUs (%)	–	2.8	−1.5	2.5
HI	0.04	0.03	0.03	0.03
CI	0.99	0.99	0.99	0.99

(b) Prescribed dose of 48 Gy/4 fr (12 Gy/fr)

Phantom offset RL (cm)	0.0	−2.5	−5.0	−7.5
Max dose (Gy)	49.88	50.35	49.35	49.84
Min dose (Gy)	45.9	47.79	46.67	47.78
Mean dose (Gy)	49.11	49.15	48.91	48.93
Time (s)	444.1	467.2	425.5	432.2
Difference of Irradiation time (%)	–	5.2	−4.2	−2.7
MUs	6290	6625	6020	6121
Difference of MUs (%)	–	5.3	−4.3	−2.7
HI	0.04	0.04	0.03	0.03
CI	0.98	0.97	0.97	0.97

3.2. Method 2. Influence of the phantom offset along the RL and AP directions on dosimetric parameter and irradiation time

The influence of the phantom offset along the RL direction on the dosimetric parameter and irradiation time is shown in Table 3. The dosimetric parameter, irradiation time and MUs were not affected by phantom offset with prescribed doses of 2 and 12 Gy/fr.

The influence of the phantom offset along the AP direction on dosimetric parameter and irradiation time is shown in Table 4. The irradiation times and MUs were increased at most 9.3% and 10.8%, respectively, by phantom offset with a prescribed dose of 2 Gy/fr. Alternatively, the irradiation times and MUs increased at most 7.2% and 7.3%, respectively by phantom offset with prescribed dose of 12 Gy/fr.

Table 4
Influence of phantom offset along the AP direction on irradiation conditions.

(a) Prescribed dose of 50 Gy/25 fr (2 Gy/fr)

Phantom offset AP (cm)	−5.0	−2.5	0.0	2.5	5.0
Max dose (Gy)	52.65	52.38	52.32	52.09	52.20
Min dose (Gy)	49.75	49.78	48.19	47.97	49.60
Mean dose (Gy)	51.14	51.18	51.37	50.80	50.94
Time (s)	90.1	88.8	82.4	89.7	85.6
Difference of Irradiation time (%)	9.3	7.8	–	8.9	3.9
MUs	1161	1141	1048	1153	1094
Difference of MUs (%)	10.8	8.9	–	10.0	4.4
HI	0.04	0.04	0.04	0.03	0.04
CI	0.99	1.00	0.99	0.98	0.99

(b) Prescribed dose of 48 Gy/4 fr (12 Gy/fr)

Phantom offset AP (cm)	−5.0	−2.5	0.0	2.5	5.0
Max dose (Gy)	49.49	49.6	49.88	49.47	49.24
Min dose (Gy)	47.49	47.5	45.9	45.55	47.72
Mean dose (Gy)	48.47	49.05	49.11	48.5	48.45
Time (s)	476.1	464.9	444.1	473.8	433.9
Difference of Irradiation time (%)	7.2	4.7	–	6.7	−2.3
MUs	6751	6718	6290	6718	6146
Difference of MUs (%)	7.3	6.8	–	6.8	−2.3
HI	0.03	0.03	0.04	0.03	0.03
CI	0.96	0.99	0.99	0.94	0.96

Table 5
Comparison of irradiation time with and without phantom offset along the RL direction.

Phantom offset RL (cm)	Prescribed dose	0.0	−2.5	−5.0	−7.5
Difference of Irradiation time (%)	2 Gy/fr	–	−0.6	10.7	14.5
	12 Gy/fr	–	7.0	−9.9	−15.1

Table 6
Comparison of irradiation time with and without phantom offset along the AP direction.

Phantom offset AP (cm)	Prescribed dose	−5.0	−2.5	0.0	2.5	5.0
Difference of Irradiation time (%)	2 Gy/fr	9.9	−7.0	–	−5.8	13.9
	12 Gy/fr	−6.2	−1.8	–	5.9	−15.0

3.3. Impacts of PTV offset vs. Phantom offset along the RL and AP directions on irradiation time

Comparisons of the impact of PTV offset and phantom offset on irradiation time are shown in Table 5 along the RL direction and Table 6 along the AP direction. The irradiation time of the PTV offset was longer than that of the phantom offset for both prescribed doses of 2 and 12 Gy/fr. For the prescribed dose of 2 Gy/fr, in the results in the RL direction, the nonparametric Wilcoxon signed-rank test showed a not significant difference between Method 1 and 2 (the maximum dose, $p = 0.750$; minimum dose, $p = 1.000$; mean dose, $p = 0.500$; irradiation time, $p = 0.500$; MUs, $p = 0.500$; HI, not calculated; and CI, $p = 0.149$), and there were no significant differences in these values between the Method 1 and 2 in the AP direction (the maximum dose, $p = 0.125$; minimum dose, $p = 0.625$; mean dose, $p = 0.875$; irradiation time, $p = 0.625$; MUs, $p = 0.625$; HI, $p = 0.584$ and CI, $p = 1.000$). Alternatively, for the prescribed dose of 12 Gy/fr, in the results of RL direction, the nonparametric Wilcoxon signed-rank test showed a non-significant difference in these values between Method 1 and 2 (the maximum dose, $p = 0.500$; minimum dose, $p = 0.750$; mean dose, $p = 0.250$; irradiation time, $p = 0.750$; MUs, $p = 0.500$; HI, $p = 0.500$; and CI, $p = 0.500$), and there were no significant differences in these values between Method 1 and 2 in the result of AP direction (the maximum dose, $p = 0.625$; minimum dose, $p = 0.625$; mean dose, $p = 0.625$; irradiation time, $p = 0.375$; MUs, $p = 0.625$; HI, not calculate and CI, $p = 0.371$). However, there was an increase in likelihood of longer irradiation time when the distance from GIC to the PTV was ≥5 cm.

4. Discussion

In this study, we clarified the influence of the offset distance of the PTV and phantom from the GIC on dosimetric parameter and irradiation time in TomoTherapy. There was no significant difference in the maximum dose, minimum dose, mean dose, HI, or CI values with or without offset along RL and AP directions, indicating the dosimetric parameter was not affected by offsetting both the PTV and phantom. Alternatively, a PTV offset increased the irradiation time and MUs, and the increases for a prescribed dose of 2 Gy/fr were greater than those at 12 Gy/fr due to the difference in the pitch factor [13]. The increase of irradiation time should be noted since some reports suggest this increase might increase the possibility of occurrence of secondary cancers and a myelodysplastic syndrome [14–16].

Many factors influence the irradiation time in IMRT treatment plans because of the complicated nature of TomoTherapy planning. Chen et al. [13] suggested that a longitudinal pitch-dependent dose ripple artifact is the optimal model to reduce the threading effect. Furthermore, Shimizu et al. [17] and Kawashima et al. [18] reported that MF and grid size affected the irradiation time. The pitch and field width are the same concept as the pitch and slice width are used for diagnostic helical CT, and the irradiation time is reduced if these factors are increased. MF could affect the irradiation time when it is changed. However, the MF and low dose prescription might affect the dosimetric parameter and dose distribution [17]. These reports described that some parameters of IMRT treatment planning affected the irradiation conditions.

The irradiation time increased with increasing distance between the PTV position and GIC (Tables 1 and 2), causing a low minimum dose at the PTV offset of 12.5 cm, because the dose at that position was less than that with the PTV at the center of phantom (Table 1). However, with phantom offset, the irradiation times were not different in the RL and AP directions (Tables 3 and 4). Various factors, such as the shape of the phantom and absorption of the couch, are involved in the difference between the RL direction and AP direction, so it is difficult to compare with the elliptical phantom assuming the trunk. Longer irradiation times were not observed when the offsets of the phantom and PTV were aligned with the GIC. The irradiation time was reduced when the PTV was aligned with the GIC or the PTV offset was less than 5 cm (Tables 5 and 6). On the AP axis, the offset could be performed with high accuracy by moving the treatment couch up and down more than 2.0 cm, but the RL axis did not have enough offset distance. These results indicate that increasing the irradiation time could be avoided by aligning the PTV with the GIC using an off-settable index bar such as the HM-bar [6,8].

Diallo et al. [19] reported distribution of second malignant neoplasm that 12% of the central area of the PTV, 66% of that within 5 cm of the PTV, and 22% of that in regions more than 5 cm from the PTV induced cancer in childhood radiotherapy. This indicates the importance of out-of-field doses 5 cm or more away from the target. We previously showed that several mGy of irradiation was administered to the head and neck in a case of prostate IMRT treatment [20]. A longer irradiation time is positively associated with out-of-field dose, which indicates that increasing the irradiation time increases the risk of secondary cancers in out-of-field areas [20]. TG-158 suggested that many factors could cause secondary cancers. We propose that irradiation time (beam on time) in the IMRT plan is one such factor in TomoTherapy [16].

Finally, the increased irradiation time shown in this study may also be found in other radiotherapy systems that use an O-ring design, such as Radixact (Accuray Inc., Sunnyvale, CA) and Halcyon (Varian Medical Systems, Palo Alto, CA). For example, in the Halcyon design, the treatment couch can be offset ± 20 cm from the isocenter [21]. However, the treatment couch movement is limited according to the need for the location of the PTV to be near the GIC [22]. It is important to offset CT-simulation with a low-attenuation index bar, such as a HM-bar, to move the PTV closer to the GIC. These improvements are valuable because increased irradiation time and MUs can increase the secondary cancer risk of radiotherapy systems that use an O-ring design.

5. Conclusions

A PTV location offset ≥5 cm from the GIC along the RL and AP axes increasing the irradiation time and MUs, should be aligned with the GIC as much as possible to reduce irradiation time and MUs on TomoTherapy.

Acknowledgements

Funding: This work was supported by a JSPS KAKENHI [grant number JP17K09071]. MH is in receipt of a Kindai university student ship. We thank Richard Lipkin, PhD, and Ashleigh Cooper, PhD, from Edanz Group (www.edanzediting.com/ac) for editing a draft of this manuscript.

Declaration of Competing Interest

None.

References

[1] Jeraj R, Mackie TR, Balog J, Olivera G, Pearson D, Kapatoes J, et al. Radiation characteristics of helical tomotherapy. Med Phys 2004;31:396–404. https://doi.org/10.1118/1.1639148.

[2] Pichandi A, Ganesh KM, Jerin A, Balaji K, Kilara G. Analysis of physical parameters and determination of inflection point for Flattening Filter Free beams in medical linear accelerator. Reports Pract Oncol Radiother 2013;19:322–31. https://doi.org/10.1016/j.rpor.2014.01.004.

[3] Langen KM, Papanikolaou N, Balog J, Crilly R, Followill D, Goddu SM, et al. QA for helical tomotherapy: Report of the AAPM Task Group 148. Med Phys 2010;37:4817–53. https://doi.org/10.1118/1.3462971.

[4] Diamond Traffic Products. TomotherapyUserGide_1014907-ENG 2014.

[5] Xu Y, Yan H, Hu Z, Ma P, Men K, Huang P, et al. Influence of tumor location on the intensity-modulated radiation therapy plan of helical tomotherapy. Med Dosim 2017;42:334–40. https://doi.org/10.1016/J.MEDDOS.2017.07.003.

[6] Monzen H, Kubo K, Tamura M, Hayakawa M, Nishimura Y. Development of a novel low-radiation-absorbent lok-bar to reduce X-ray scattering and absorption in RapidArc® treatment planning and dose delivery. J Appl Clin Med Phys 2017;18:44–51. https://doi.org/10.1002/acm2.12066.

[7] Olch AJ, Gerig L, Li H, Mihaylov I, Morgan A. Dosimetric effects caused by couch tops and immobilization devices: report of AAPM Task Group 176. Med Phys 2014;41:061501https://doi.org/10.1118/1.4876299.

[8] Hirata M, Monzen H, Tamura M, Kubo K, Matsumoto K, Hanaoka K, et al. Impact of the Lok-bar for high-precision radiotherapy with tomotherapy. Anticancer Res 2018;38:2733–8. https://doi.org/10.21873/anticanres.12515.

[9] Weyh A, Konski A, Nalichowski A, Maier J, Lack D. Lung SBRT: dosimetric and delivery comparison of RapidArc, TomoTherapy, and IMRT. J Appl Clin Med Phys 2013;14:3–13.

[10] Oliver M, Ansbacher W, Beckham WA. Comparing planning time, delivery time and plan quality for IMRT, RapidArc and tomotherapy. J Appl Clin Med Phys 2009;10:117–31. https://doi.org/10.1120/jacmp.v10i4.3068.

[11] Li MH, Huang SF, Chang CC, Lin JC, Tsai JT. Variations in dosimetric distribution and plan complexity with collimator angles in hypofractionated volumetric arc radiotherapy for treating prostate cancer. J Appl Clin Med Phys 2018;19:93–102. https://doi.org/10.1002/acm2.12249.

[12] Kanda Y. Investigation of the freely available easy-to-use software 'EZR' for medical statistics. Bone Marrow Transplant 2013;48:452–8. https://doi.org/10.1038/bmt.2012.244.

[13] Chen M, Chen Y, Chen Q, Lu W. Theoretical analysis of the thread effect in helical TomoTherapy. Med Phys 2011;38:5945–60. https://doi.org/10.1118/1.3644842.

[14] Radivoyevitch T, Sachs RK, Gale RP, Molenaar RJ, Brenner DJ, Hill BT, et al. Defining AML and MDS second cancer risk dynamics after diagnoses of first cancers treated or not with radiation. Leukemia 2016;30:285–94. https://doi.org/10.1038/leu.2015.258.

[15] Hall EJ, Wuu C-S. Radiation-induced second cancers: the impact of 3D-CRT and IMRT. Int J Radiat Oncol 2003;56:83–8. https://doi.org/10.1016/S0360-3016(03)00073-7.

[16] Kry SF, Bednarz B, Howell RM, Dauer L, Followill D, Klein E, et al. AAPM TG 158: Measurement and calculation of doses outside the treated volume from external-beam radiation therapy. Med Phys 2017;44:e391–429. https://doi.org/10.1002/mp.12462.

[17] Shimizu H, Sasaki K, Tachibana H, Tomita N, Makita C, Nakashima K, et al. Analysis of modulation factor to shorten the delivery time in helical tomotherapy. J Appl Clin Med Phys 2017;18:83–7. https://doi.org/10.1002/acm2.12075.

[18] Kawashima M, Kawamura H, Onishi M, Takakusagi Y, Okonogi N, Okazaki A, et al. The impact of the grid size on TomoTherapy for prostate cancer. J Med Phys 2017;42:144–50. https://doi.org/10.4103/jmp.JMP_123_16.

[19] Diallo I, Haddy N, Adjadj E, Samand A, Quiniou E, Chavaudra J, et al. Frequency distribution of second solid cancer locations in relation to the irradiated volume among 115 patients treated for childhood cancer. Int J Radiat Oncol Biol Phys 2009;74:876–83. https://doi.org/10.1016/j.ijrobp.2009.01.040.

[20] Hirata M, Monzen H, Hanaoka K, Nishimura Y. Measurement of absorption dose outside irradiation field in IMRT. Radiat Prot Dosimetry 2017;176:425–33. https://doi.org/10.1093/rpd/ncx027.

[21] Halcyon V1 Specifications. (n.d.). Retrieved from http://photonix.com.ar/wp-content/uploads/2018/10/halcyon-specifications.pdf. California: n.d.

[22] Guide P, Halcyon C, Eclipse P, Rtm A, Components P. Halcyon Planning Workflow n.d.