Iranian Journal of Medical Physics

ijmp.mums.ac.ir

Dosimetric Effect Resulting From the Collimator Angle, the Isocenter Move, and the Gantry Angle Errors

Yassine Oulhouq[1], Abdeslem Rrhioua[2*], Mustapha Zerfaoui[2], Dikra Bakari[3]

1. HASSAN II Oncology Center, University Hospital Mohammed VI & LPMR, Faculty of sciences, University Mohamed 1st, Oujda, Morocco
2. LPMR, Faculty of sciences, University Mohamed 1st, Oujda, Morocco
3. National School of Applied Sciences, University Mohamed 1st, Oujda, Morocco

ARTICLE INFO

Article type:
Original Article

Article history:
Received: Nov 18, 2018
Accepted: Feb 18, 2019

Keywords:
Collimator Angle
Dosimetry
Granty Angle
Head and Neck
LINAC
Radiotherapy

ABSTRACT

Introduction: Dose distribution can be affected by diverse parameters, such as beam orientations, and collimator angles. These parameters should respect and maintain the international recommended levels during the realization of the quality assurance protocols of linear accelerators. This study aimed at evaluating the dosimetric effects on treatment quality considering the mechanical error fluctuations in the recommended range.

Material and Methods: This study included ten patients with head and neck cancer. All of them were treated using three-dimensional conformal radiotherapy with the simple 3-field classic technique. Initially, an optimized treatment plan was computed for each patient. Afterward, similar calculations were executed by varying isocenter position, gantry and collimator angles. Eventually, dosimetric evaluations based on dose-volume histograms were studied and analyzed by Wilcoxon signed rank test for each plan.

Results: The analysis of the dose-volume histograms of tumor volumes and organs at risk, as well as the dosimetry calculation, revealed that the small errors of 0.5° in gantry and collimator angles have minimal effects on dose distribution. However, the variation in isocenter coordinating up to 1 mm may influence the patients' treatment quality, particularly in the spinal cord and the brainstem, in which Wilcoxon's test showed significant effects in all plans.

Conclusion: According to the results, the quality of the treatment plans is almost insensitive to the errors of the gantry and the collimator angles of the order 0.5° though it is relatively sensitive to isocenter errors (1 mm). These should be reduced in order to avoid overdose when applying the conventional 3-field technique.

► *Please cite this article as:*
Oulhouq Y, Rrhioua A, Zerfaoui M, Bakari D. Dosimetric Effect Resulting From the Collimator Angle, the Isocenter Move, and the Gantry Angle Errors. Iran J Med Phys 2019; 16: 355-361. 10.22038/ijmp.2019.30616.1350

Introduction

The quality assurance of radiotherapy treatments is automatically correlated with patient safety. As the objective is to ensure that the exposure of normal tissue is kept as low as reasonably achievable, it must be consistent with the delivering of the required dose to the planning target volume (PTV) [1].

Currently, clinical observations have indicated that the majority of treatment failures, after radiation therapy, are manifested by local relapse as the first sign [2-4]. Therefore, the measures to ensure the quality of a radiotherapy treatment inherently provide safety for patients and avoid accidental exposure. Recent technological advances in computer applications and linear accelerator (LINAC) technology have provided new devices to produce and deliver optimized radiation treatments [5].

In Africa, most radiotherapy centers are fairly basic. They mostly offer palliative care and simple curative treatments based on two-dimensional imaging and treatment planning [6]. Approximately, 80% of centers are small with one or two radiotherapy machines and basic equipment for imaging and treatment planning [7]. Some advanced centers are equipped with modern imaging tools, treatment systems, and more complex radiotherapy procedures, such as three-dimensional conformal radiotherapy (3D-CRT). These centers are able to do intensity-modulated radiotherapy and image-guided procedures. However, the later accounts for only about 2% of radiotherapy centers in Africa [7]. Accordingly, the focus will be on the 3D-CRT treatment in this study. In practice, the conformal three-dimensional radiation therapy plans are usually obtained using treatment planning system (TPS) in which the final dose distributions are determined by many beam parameters, such as beam orientations, and collimator angles.

These latter parameters have to respect certain constraints and tolerances during the realization of the quality assurance protocols of linear accelerators.

*Corresponding Author: Tel: +212 536 500 601; Fax: +212 536 500 603; Email: a.rrhioua@ump.ac.ma

They are issued by the International Organization for Medical Physics [8-12] in order to ensure that the accurate dose has been delivered in the defined volume.

With this background in mind, this study carefully examined the dose distributions accuracy delivered to patients with head and neck cancer and analyzed the dosimetric effect resulted from the collimator angle, the isocenter move, and the gantry angle errors. To this end, six non-equally spaced coplanar beams were used for the treatment and they were divided into three series of treatments.

Materials and Methods

This study included 10 patients with head and neck cancer for which planning targets have been contoured for gated treatments. The prescription dose has been defined as the dose that covered 95% of the planning target volume [13]. Targets contoured for each patient had 3D-CRT plans; therefore, the prescribed dose increased to the upper limit which was below the dose constraints of the organs at risk.

All plans were calculated with the Analytical Anisotropic Algorithm (AAA) using Eclips 13.6 TPS. The planned doses include 70 Gy, 2 Gy/fraction, and 5 fractions/week to a reference point in the PTV. A simple 3-field classic technique (two lateral opposed fields abutted to an anterior low-neck field) was utilized through adding electron beams to match the photon fields (Figure 1) in order to spare the spinal cord when delivering doses larger than 45 Gy [14,15].

The superficial tissues in the shielded area were treated with the electron beams of energy insufficient to cause further significant irradiation of the spinal cord (6-12 MeV).However, the incident photon beam energy was 6 MV generated using a Clinac 2100 C (Varian Oncology System).

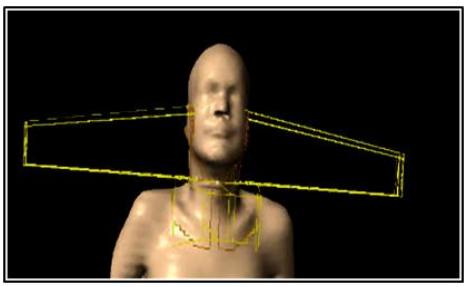

Figure 1. Simulation of treatment beams

After obtaining the optimal treatment plan for each patient, incident beam parameters were purposely varied in all fields and for each treatment plan. These parameters cover the gantry angle, the collimator angle, and the isocenter position, while keeping the other beam parameters fixed and respecting tolerances list established by the American Association of Physicists in Medicine (AAPM) TG 142 [12].

Subsequently, the dose distributions and relevant dosimetric quantities were compared regarding the variation parameter for each beam. For each patient, 11 treatment plans were constructed in three-dimensional conformational radiotherapy. The reference plan was the first one in which the dose was calculated using the AAA algorithm without introducing any mechanical error. The plans, from the second to the seventh, represented comparison plans in which the dose was successively calculated by introducing one of the mechanical errors of the gantry, the collimator, and the isocenter.

For the eighth, ninth and tenth plans, the doses were successively calculated by introducing the sum of the errors of gantry + isocenter, gantry + collimator, and collimator + isocenter. Whereas, the dose for the eleventh plan was calculated considering the sum of all errors (gantry + collimator + isocenter).

Table 1 presents all the various changes and tolerances.

Table 1. Studied plans

Plans	
1	Reference plan
2	Plan with a deviation of gantry angle by + 0.5° from the reference plan
3	Plan with a deviation of collimator angle by +0.5° from the reference plan
4	Plan with an isocenter move by +1mm (relative to the OY axis) from reference plan
5	Plan with a deviation of gantry angle by - 0.5° from the reference plan
6	Plan with a deviation of collimator angle by -0.5° from the reference plan
7	Plan with an isocenter move by -1mm (relative to the OY axis) from reference plan
8	Association of the plans2 and 4.
9	Association of the plans 2 and 3.
10	Association of the plans3 and 4.
11	Association of the plans 2, 3, and 4.

The isodose curves computed for the treatment in the axial and sagittal plans and the DVHs of target and organs at risk are evaluated for each patient and configuration. The maximum, minimum, and average dose to the target and sensitive structures are recorded. These parameters are used to calculate the homogeneity (HI) and the conformity (CI) indices of radiation. The HI and CI are two analysis tools of a treatment plan using conformal radiotherapy. They are used to estimate the degree of congruence between tumor contour and healthy tissue contour isodoses through geometric intersection methods [16,17]. The quality indices are defined as follows:

$$\text{Conformity Index}_{RTOG} = V_{RI}/TV \quad (1)$$

Where, V_{RI} signifies the reference isodose volume and TV denotes the target volume. Plans are not deviating from the RTOG protocol if the conformity index value is between 1.0 and 2.0. They are with minor deviations if the conformity index value is between 2.0 and 2.5. However, the plans with a conformity index

value greater than 2.5 or less than 0.9 are considered as having major deviations.

$$\text{Homogeneity Index}_{RTOG} = I_{max}/RI \quad (2)$$

Where, I_{max} indicates the maximum isodose in the target, and RI is the reference isodose. Plans with homogeneity index less than or equal to 2 do not deviate from the protocol. Those with homogeneity index value between 2 and 2.5 are with minor deviations. While plans with HI value greater than 2.5 are considered with major deviations.

Another alternative conformity index to the RTOG conformity index developed by Lomax and Scheib [18] was also calculated. Lomax and Scheib's modified index, CI_{Lomax} is calculated as:

$$CI_{Lomax} = TV_{PIV}/TV \quad (3)$$

Where, TV_{PIV} signifies the target volume covered by the prescription isodose and TV denotes the target volume. This index shows the proportion of the target volume that receives the minimum prescription dose. This conformity index can range from 0 to an optimum value of 1 when the target volume receives at least the prescribed dose in its entirety.

Results

In order to study the effect of the isocenter position, gantry, and collimator rotations, DVHs were calculated for the eleventh plans for each patient. Table 2 summarizes the comparison of the maximum, mean, and minimum doses collected from DVH of the PTV which are utilized to calculate and compare the RTOG homogeneity and conformity indices of radiation (Tables 3-5).

Moreover, the DVHs and maximum doses of spinal cord and brainstem calculated from the eleventh plan are compared with the reference plan. Furthermore, the sagittal and coronal profile doses in the eleventh plans for each patient are compared and given in Tables 6-8. The differences are analyzed by Wilcoxon signed rank test which is the simplest of all the nonparametric methods [19].

The Wilcoxon sign-rank test is employed in this study to compare the dosimetric changes on the plans regarding mechanical errors (plans 2-11) as well as the reference plan. For each patient, 10 error treatment plans are compared according to the following parameters. Table 2 displays the minimum, mean, and maximum PTV doses. The Wilcoxon test was also applied on spinal cord and brainstem maximum doses. For each parameter, the Wilcoxon signed-rank test was used to determine any statistically significant difference. P-value less than 0.05 was considered statistically significant.

The changes in the PTV dose are not significant for the angulation errors of gantry and collimator. However, the isocenter error causes a light dose change, compared to those caused by the other parameters. It is also noticed that the dose increases when more than one parameter is modified. Concerning the DVH representation (Figure 2), it is observed that its shape remarkably changes, compared to the reference plan when changing the isocenter alone or simultaneously with another parameter. However, the statistical analysis showed no significant impact of isocenter, gantry, and collimator angle errors on dosimetric plans for a minimum, mean, and maximum doses of all plans ($P>0.05$).

In addition, Tables 3-5 summarize the quality indices for all patients in all plans (i.e., 1-11). The comparison between reference plan and other plans showed no significant impact of mechanical errors on quality plans for CI, CI_{Lomax}, and HI for all patients.

Table 2. Comparative analysis of minimum, mean, and maximum doses for PTV

PLANS		1	2	3	4	5	6	7	8	9	10	11
Hotspot		75.87	75.98	75.98	75.88	75.96	75.96	76.09	75.9	75.96	75.9	75.89
	Mean	55.7	56.71	56.8	57.92	56.87	56.74	55.19	57.87	57.02	58.05	58.08
Minimum	P-Value	-	0.484	0.889	0.176	0.484	0.575	0.208	0.123	0.889	0.123	0.123
	Mean	70.26	70.27	70.26	70.29	70.26	70.24	70.19	70.32	70.26	70.32	70.31
Mean	P-Value	-	0.779	0.327	0.31	0.889	0.779	0.208	0.208	0.833	0.093	0.263
	Mean	74.4	74.42	74.41	74.31	74.41	74.37	74.5	74.35	74.41	74.33	74.35
Maximum	P-Value	-	0.575	0.611	0.028	0.779	0.611	0.123	0.161	0.483	0.123	0.161

Table 3. Comparison of the RTOG conformity index for each patient

	Plan1	Plan2	Plan3	Plan4	Plan5	Plan6	Plan7	Plan8	Plan9	Plan10	Plan11
Patient1	1.42	1.43	1.43	1.43	1.43	1.43	1.44	1.42	1.42	1.42	1.4
Patient2	1.31	1.26	1.24	1.22	1.27	1.25	1.31	1.20	1.26	1.21	1.19
Patient3	2.38	2.34	2.39	2.31	2.34	2.35	2.52	2.28	2.36	2.33	2.28
Patient4	2.50	2.50	2.50	2.36	2.51	2.49	2.49	2.43	2.42	2.43	2.42
Patient5	1.89	1.99	1.98	1.97	1.98	1.98	1.98	1.98	1.99	1.97	1.98
Patient6	1.89	1.83	1.91	1.86	1.89	1.91	1.90	1.84	1.83	1.86	1.85
Patient7	2.39	2.39	2.39	2.40	2.39	2.39	2.39	2.39	2.39	2.40	2.39
Patient8	1.78	1.78	1.78	1.78	1.78	1.78	1.77	1.78	1.78	1.78	1.78
Patient9	1.79	1.87	1.87	1.88	1.87	1.88	1.8	1.87	1.89	1.86	1.88
Patient10	2.16	2.13	2.18	2.11	2.12	2.14	2.31	2.16	2.16	2.14	2.18

Table 4. Comparison of the conformity index proposed by Lomax and Scheib (CI_{Lomax}) for each patient

	Plan1	Plan2	Plan3	Plan4	Plan5	Plan6	Plan7	Plan8	Plan9	Plan10	Plan11
Patient1	0.97	0.97	0.96	0.97	0.96	0.96	0.95	0.98	0.96	0.97	0.97
Patient2	0.99	0.97	0.96	0.99	0.97	0.96	0.94	0.99	0.97	0.99	0.99
Patient3	0.98	0.98	0.98	0.99	0.98	0.97	0.95	0.99	0.98	0.99	0.99
Patient4	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Patient5	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97
Patient6	1	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Patient7	0.99	0.99	0.99	1	1	0.99	0.99	1	0.99	1	1
Patient8	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Patient9	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Patient10	0.98	0.98	0.98	0.99	0.98	0.97	0.95	0.99	0.98	0.99	0.99

Table 5. Comparison of the homogeneity index for each patient

	Plan1	Plan2	Plan3	Plan4	Plan5	Plan6	Plan7	Plan8	Plan9	Plan10	Plan11
Patient1	1.108	1.103	1.107	1.103	1.106	1.107	1.106	1.106	1.106	1.105	1.1
Patient2	1.088	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
Patient3	1.099	1.097	1.098	1.098	1.098	1.0988	1.097	1.097	1.097	1.098	1.097
Patient4	1.117	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Patient5	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Patient6	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Patient7	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Patient8	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.13	1.13	1.12
Patient9	1.115	1.114	1.117	1.115	1.115	1.117	1.114	1.115	1.115	1.114	1.115
Patient10	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.109	1.109	1.11	1.11

Table 6. Spinal cord comparison of plan reference maximum dose with other plans

PLANS	1	2	3	4	5	6	7	8	9	10	11
Max	46.238	46.185	46.219	48.193	46.352	46.233	45.336	48.104	46.195	48.184	48.131
Mean	45.94	46.13	46.19	48.03	46.19	46.16	44.76	47.85	46.30	47.97	47.95
Median	46.24	46.28	46.37	48.19	46.37	46.27	45.09	48.14	46.33	48.19	48.13
SD	1.677	1.905	1.846	2.040	1.896	1.893	1.526	2.182	1.765	2.158	2.150
P-Value	-	0.674	0.093	0.012	0.025	0.093	0.012	0.012	0.123	0.012	0.012

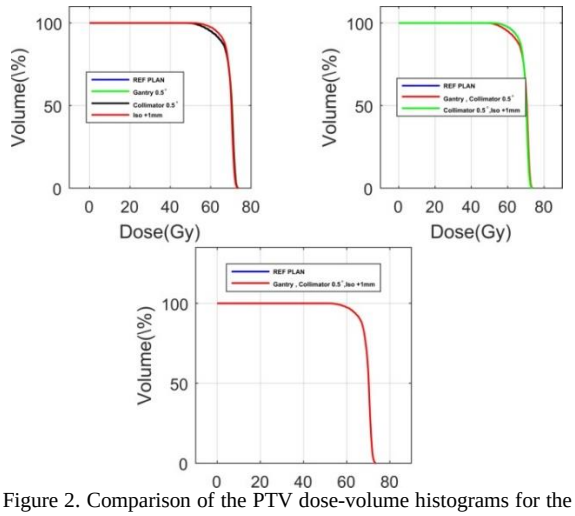

Figure 2. Comparison of the PTV dose-volume histograms for the eleventh treatment plan of patient 1

Spinal Cord

In this study, the recommended dose constraints for the spinal cord (i.e., D_{max}< 45 Gy and D_{max}< 50Gy) are considered for every case in the reference plans. Moreover, in the other plans after modifying one or several parameters, the maximum dose exceeds 46 Gy, especially in the plans with the 1mm tolerable error of the isocenter. It is noted that the maximum dose can reach 48.19 and 48.13 Gy in the case of the fourth and eleventh plan, respectively, as well as the plan where there is the sum of three mechanical errors.

The result of the Wilcoxon test demonstrates a significant difference between the different study plans, compared to the reference plan. Table 6 presents the dosimetric and statistical results for the maximum doses received by the spinal cord.

According to the Wilcoxon statistical test, no significant statistical difference was observed in terms of D_{max} calculated at the spinal cord for plans 2, 3, 6 and 9. However, Wilcoxon test results obtained from the other plans show a significant difference regarding the patients' set, P<0.05.The spinal cord DVH of different plans was compared in order to study the mechanical error effects. Figure 3 illustrates the obtained DVH.

Brainstem

The brainstem is responsible for several functions, including regulating breathing, and heart rate. Complications related to brainstem irradiation are classified according to their clinical presentation and their onset after irradiation. Therefore, acute semi-delayed and late complications are described and related to different physio-pathogenic mechanisms [20-24].

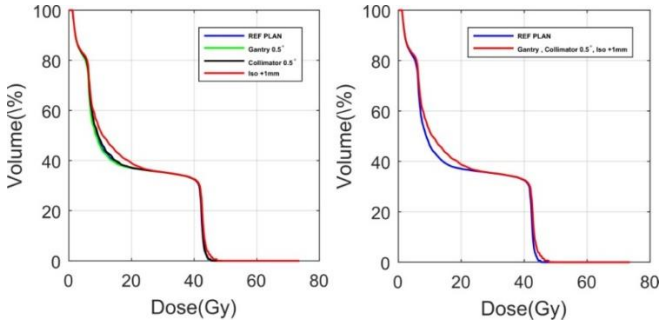

Figure 3. Comparison of the spinal cord dose-volume histograms for the eleventh treatment plans of patient 1

Table 7. Comparison of brainstem maximal dose

PLANS	1	2	3	4	5	6	7	8	9	10	11
Mean	57.01	57.22	57.11	58.94	57.15	57.08	55.61	58.65	57.63	58.56	58.66
P-Value	-	0.575	1.000	0.012	0.779	0.208	0.017	0.012	0.208	0.012	0.012

Table 8. Comparison of brainstem D1-10cc dose

Plans / Patients	1	2	3	4	5	6	7	8	9	10	11
1	50.3	50.2	50.1	50.8	50.1	50.1	49.5	50.6	50.2	50.8	50.8
2	48.1	47.7	47.6	48.5	47.6	47.6	46.8	48.6	47.7	48,5	48.6
3	53.9	53.8	54.3	57.1	53.8	53.5	45.4	57.1	54.2	57.5	57.5
4	40	40	40	42.9	40	40	39.9	41.2	41.2	41.1	41.2
5	50.5	51.5	51.6	53.2	51.3	51.6	50.1	53.2	51.5	53.2	53.2
6	34.6	34.5	34.6	34.7	34.6	34.5	34.4	34.7	34.6	34.8	34.8
7	56.5	56.6	56.6	59.1	56.8	56.5	53.6	59.2	56.7	59.1	59.2
8	56.9	56.8	56.8	59.8	56.8	56.7	54.6	59.8	56.8	59.8	59.8
9	50	50	50	52.8	50	50.02	49.79	51.4	51.4	51.4	51.4
10	54.7	54.6	55.6	58.3	54.7	54.5	50.2	58.3	55.2	58.3	58.3

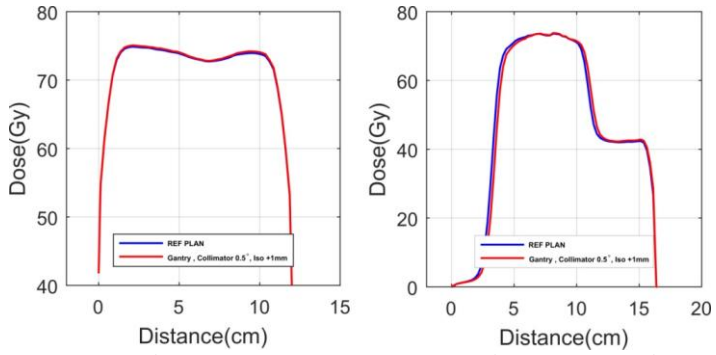

Figure4. Lateral (left) and vertical (right) dose distribution for various plans of patient 1

The maximal dose recommended for brainstem in conventional fractionation and spreading is 54 Gy [25] and a small volume (1 to 10 ml) can be irradiated at a maximal dose of 59 Gy with a conventional fractionation of 2 Gy [26].

According to the result of the Wilcoxon test, the difference is not statistically significant for the isocenter error plans (i.e., Plans 4, 7, 8, 10 and 11, Table 7). For the other treatment plans, certain types of errors have the same dosimetry quality with a risk equal to 5%.

Afterward, the volume dose D1-10 cc of the brainstem was compared regarding the reference plan and others to quantify the effect of mechanical errors on the brainstem. It is noted that D1-10 cc which connotes smaller volumes of the brainstem (1–10 cc) may be irradiated to a maximum dose of 59 Gy with conventional dose fraction (2Gy) [27].

Table 8 shows no significant difference between the reference plan and plans 2, 3, 5, 6, and 9 for all patients. Nevertheless, there is a significant difference regarding plans 4, 7,8, 10, and 11 which connotes the isocenter error. It is clear that the dose may exceed 59.2 Gy in plan 11 considering the gantry angle, collimator, and the isocenter errors at the same time. As an example, D1-10

exceed 59.2 Gy in plan 11 besides 56 Gy in the reference plan in patient 7.

A comparison was performed between two profiles taken from a scanned image in a region in which the dose difference was clear between the reference plan and the other one. Figure 4 illustrates these curves.

The general appearances of the horizontal profiles are similar; however, there are slight differences within the plans (2-11) considering the mechanical errors.

Moreover, the dose profile in the horizontal direction is identical for all plans (1-11). However, there are differences between the vertical profile and the reference plan in terms of the curves of the plans regarding the gantry and collimator errors. On the other hand, considering the isocenter error, a significant difference is observed between the reference plan curves and those of the isocenter error (Figure 4).

Discussion

According to the results, the dose deviations of the PTV are very less sensitive in plans with the angulation errors of the gantry, collimator, and the isocenter. In addition, there are remarkable deviations in the minimum dose of the PTV caused by the isocenter error (plans 4, 8, 9 and 11).

On the other hand, mechanical errors do not cause any remarkable dose changes in the homogeneity index. The maximum dose of the spinal cord was compared with that of the brainstem. These organs are serially functioning normal structures [28], and the D_{max} is the most important biological response.

The spinal cord will be damaged and lose its function if one of its sub-volumes is damaged [29, 30] therefore, in the DVH data used for the spinal cord, the dose constraints for this organ is D_{max}< 45 Gy [31-,32]. When avoiding complications, it is also recommended to respect a maximum dose of 50 Gy [33].

The results show the absence of a significant clinical impact on these two OARs between the reference plan and the plans with errors of collimator and gantry rotation angle. However, in the majority of patients, the difference in D_{max} is remarkable for the other plans with an isocenter error.

Nevertheless, it is demonstrated that errors on the isocenter parameter that exceeds 1 mm can produce significant modifications in the dose distribution. Indeed, there is a clear difference between the DVH and the dose profiles of the PTV and the spinal cord, calculated for the reference plan and the one that takes into account the isocenter error.

It can be concluded that for the classic technique using the simple 3-field, the threshold errors of 0.5° for collimator and gantry rotation angle cannot affect the quality of treatment plans. At variance, the threshold of 1mm for the isocenter parameter can affect the treatment plan for the patients with head and neck cancer, especially in the case of dose max of the spinal cord and brainstem.

Conclusion

The dose distribution was investigated regarding the isocenter position, the gantry, and collimator angle errors. These mechanical errors can be associated with the inaccuracy of mechanical calibrations of the linear accelerator. Therefore, dosimetric effects were compared between the optimal treatment plans and simulated ones considering three small mechanical variations. All studied plans showed an insignificant dosimetric effect on gantry and collimator angle errors up to 0.5°. However, the isocenter position errors caused significant dosimetric changes for head and neck plans, with an overdosing of the spinal cord and brainstem. Due to the classic technique using the simple 3-field, the quality of treatment plans was less sensitive to the 0.5° errors of the gantry and collimator angles, compared to 1 mm errors of the isocenter which will be reduced leading to the avoidance of any overdose.

Acknowledgment

The authors express their gratitude and warmth thanks to Dr. Ahmed Benhabid from the University of Hull and Pr. Serraj Hachemi from the University of Oujda for their careful reading of this paper.

References

1. Thwaites DI, Mijnheer BJ, Mills JA. Quality assurance of external beam radiotherapy. Radiation oncology physics: a hand-book for teachers and students. 2005:470-50.
2. Fuks Z, Leibel SA, Wallner KE, Begg CB, Fair WR, Anderson LL, et al. The effect of local control on metastatic dissemi-nation in carcinoma of the prostate: long-term results in patients treated with 1251 implantation. Int. J. Radiat. Oncol. Biol. Phys. 1991;21(3):537-47.
3. Rubin P, Constine III LS, Nelson DF, Casarett GW. In: Rubin P, Saunders WB, editors. Clinical oncology: a multidiscipli-nary approach for physicians and students, 7th ed. New York: W.B. Saunders.1993.
4. Xing L, Lin ZX, Donaldson SS, Le QT, Tate D, Goffinet DR, et al. Dosimetric effects of patient displacement and collimator and gantry angle misalignment on intensity modulated radiation therapy. Radiother Oncol. 2000;56(1):97-108.
5. LoSasso T, Chui CS, Ling CC. Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing intensity modulated radiotherapy. Med. phys. 1998;25(10):1919-27.
6. Abdel-Wahab M, Zubizarreta E, Polo A, Meghzifene A. Improving quality and access to radiation therapy−an IAEA per-spective. In Seminars in radiation oncology. 2017; 27(2): 109-17.
7. Abdel-Wahab M, Bourque JM, Pynda Y, Iżewska J, Van der Merwe D, Zubizarreta E, et al. Status of radiotherapy resources in Africa: An International Atomic Energy Agency analysis. The lancet oncology. 2013;14(4):168-75.
8. Quality Assurance Team for Radiation Oncology. Comprehensive audits of radiotherapy practices: a

tool for quality im-provement. Vienna: International Atomic Energy Agency;2007.
9. International Atomic Energy Agency. Setting up a radiotherapy programme: clinical, medical physics, radiation protection and safety aspects. Internat. Atomic Energy Agency; 2008.
10. Aletti P, Bey P, Chauvel P, Chavaudra J, Costa A, Donnareix D,et al. Recommendations for a Quality Assurance Pro-gramme in External Radiotherapy, ESTRO.1995.
11. Kutcher GJ, Coia L, Gillin M, Hanson WF, Leibel S, Morton RJ, et al. Comprehensive QA for radiation oncology: report of AAPM Radiation Therapy Committee Task Group 40. Med Phys. 1994; 21:581‑618.
12. Klein. QA of Medical Accelerators: report of AAPM Radiation Therapy Committee Task Group 142. Med Phys. 2009; 36:4197-210.
13. Luxton G, Antony J, Loo BW, Carlson D, Maxim PG, Xing L. Dose Escalation Feasible Due to Gating in Lung Cancer Patients. Int. J. Radiat. Oncol. Biol. Phys. 2008;72(1):S625.
14. Herrassi MY, Bentayeb F, Malisan MR. Comparative study of four advanced 3dconformal radiation therapy treatment planning techniques for head and neck cancer. J Med Phys. 2013; 38:98-105.
15. Mesbahi A., Rasuli N., Nasiri B., mohammadzadeh M. Radiobiological Model. Based Comparison of Three Dimensional Conformal and Intensity Modulated Radiation Therapy Plans for Nasopharyngeal Carcinoma. Iran J Med Phys. 2017;14(4):190-6. DOI: 10.22038/ijmp.2017.22508.1213.
16. Petrova D, Smickovska S, Lazarevska E. Conformity Index and Homogeneity Index of the Postoperative Whole Breast Radiotherapy. Open Access Maced J Med Sci. 2017;5(6):736.
17. Feuvret L, Noël G, Mazeron JJ, Bey P. Conformity index: a review. Int. J. Radiat. Oncol. Biol. Phys. 2006;64(2):333-42.
18. Stanley J, Breitman K, Dunscombe P, Spencer DP, Lau H. Evaluation of stereotactic radiosurgery conformity indices for 170 target volumes in patients with brain metastases. J APPL CLIN MED PHYS. 2011;12(2):245-53.
19. Whitley E, Ball J. Statistics review 6: Nonparametric methods. Critical care. 2002; 6(6):509-13.
20. Ricard D, De Greslan T, Soussain C, Bounolleau P, SallansonnetFroment M, Delmas J.M, et al. Neurological damage of brain tumor therapy. Rev Neurol (Paris). 2008; 164:575‑87.
21. DeSalvo MN. Radiation necrosis of the pons after radiotherapy for nasopharyngeal carcinoma: diagnosis and treatment. J Radiol Case Rep. 2012; 6:9‑16.
22. Zwicker F, Roeder F, Hauswald H, Thieke C, Timke C, Schlegel W,et al. Reirradiation with intensity modulated radiothera-py in recurrent head and neck cancer. Head Neck. 2011;33(12):1695-702. DOI: 10.1002/hed.21663.
23. Hauptman JS, Barkhoudarian G, Safaee M, Gorgulho A, Tenn S, Agazaryan N, et al. Challenges in Linear Accelerator Radiotherapy for chordomas and chondrosarcomas of the skull base: focus on complications. Int. J. Radiat. Oncol. Biol. Phys. 2012; 83:542‑551.
24. Timmerman RD. An overview of hypofractionation and introduction to this issue of seminars in radiation oncology. Semin. Radiat. Oncol. 2008; 18:215‑22.
25. Guimas V, Thariat J, Graff-Cailleau P, Boisselier P, Pointreau Y, Pommier P, et al. Intensity modulated radiotherapy for head and neck cancer, dose constraint for normal tissue: Cochlea vestibular apparatus and brainstem. Cancer radiother. 2016;20(6-7):475-83.
26. Mayo C, Yorke E, Merchant TE. Radiation Associated Brainstem Injury. Int J Radiat Oncol. 2010; 76:36‑41.
27. Yao CY, Zhou GR, Wang LJ, Xu JH, Ye JJ, Zhang LF, et al. A retrospective dosimetry study of intensity-modulated radio-therapy for nasopharyngeal carcinoma: radiation-induced brainstem injury and dose-volume analysis. Radiat Oncol. 2018;13(1):194. DOI: 10.1186/s13014-018-1105-z.
28. Attalla E, Eldesoky I. The Dosimetric Effects of Different Multileaf Collimator Widths on Physical Dose Distributions. Iran J Med Phys. 2018;15(1):12-8.DOI: 10.22038/ijmp.2017.20058.1190.
29. Bahreyni Toossi MT, Rajab Bolookat E, Salek R, Layegh M. Dose measurements of parotid glands and spinal cord in conventional treatment of nasopharyngeal carcinoma using rando phantom and thermoluminescent dosimeters. Iranian J Med Phys. 2015;12(2):78-84.DOI: 10.22038/ijmp.2015.4769.
30. Adamus.Górka M, Mavroidis P, Lind BK, Brahme A. Comparison of Dose Response Models for Predicting Normal Tis-sue Complications from Cancer Radiotherapy: Application in Rat Spinal Cord. Cancers. 2011; 3(2): 2421-43. DOI:10.3390/cancers3022421.
31. McKenzie A, van Herk M, Mijnheer B. Margins for geometric uncertainty around organs at risk in radiotherapy. Radio-therapy and Oncology. 2002;62(3):299-307.
32. Majumder D, Patra NB, Chatterjee D, Mallick SK, Kabasi AK, Majumder A. Prescribed dose versus calculated dose of spinal cord in standard head and neck irradiation assessed by 3.D plan. South Asian J. Cancer. 2014; 3(1): 22-7. DOI:10.4103/2278.330X.126510.
33. Boisselier P, Racadot S, Thariat J, Graff P, Pointreau Y.Intensity modulated radiotherapy of head and neck cancers. Dose constraint for spinal cord and brachial plexus. Cancer Radiother. 2016;20(6-7):459-66. DOI: 10.1016/j.canrad.2016.08.124.