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Evaluation the Effect of Photon Beam Energies on Organ at Risk Doses in Three-Dimensional Conformal Radiation Therapy

[1]Mikaeil Molazadeh, [2]Hassan Saberi, [3]Leili Rahmatnezhad, [4]Avin Molani and [2]Nasrollah Jabbari
[1]Radiotherapy Center of Omid Hospital, Urmia, Iran
[2]Department of Medical Physics and Imaging,
[3]Department of Midwifery,
[4]Department of Medical Imaging, Urmia University of Medical Sciences, Urmia, Iran

Abstract: As regards, the selection of appropriate energy in radiotherapy tumors that are placed in non-homogen areas is important, so the aim of the present study is evaluating the effect of 6 and 15MV photon beam energies on dose distribution in 3D-CRT for lower esophageal and rectal cancers. 12 patients with lower esophageal cancer and 12 patients with rectal cancer respectively, with the prescription dose of 7000 cGy and 5040 cGy were studied. For treatment of esophagus the three-field technique and for treatment of rectum the four-field technique was used. In the thoracic area, the spinal cord and in the pelvis, the bladder and head of femurs were considered as OARs. For comparing the results, all parameters used for treatment planning except the photon beam energy were kept constant. After performing the treatment planning with two different energies in each region, the received dose rate of spinal cord, bladder and head of femurs as OARs and dose distribution in PTVs were studied. The results of this study showed that the difference between doses received by OARs in 6MV and 15MV therapeutic plans, resulted 5.2, 5.06 and -9.14%, respectively. Also the PTVs received dose difference of esophagus and rectum in the performed therapeutic plans with energy of 6 MV than energy of 15MV is 1.52 and -0.63%, respectively. We found that using of low energy photons in lower esophageal treatment and high energy photons in the rectal treatment provides the better dose coverage. Finally, with such as therapeutic plans the cumulative dose of organs at risk will be reduced.

Keywords: Lower esophageal cancer, photon beam energy, rectal cancer, three-dimensional conformal radiation therapy (3D-CRT)

INTRODUCTION

Nowadays, External Beam Radiotherapy (EBRT) is done with several new methods including Intensity Modulated Radiation Therapy (IMRT), helical thomotherapy, three-dimensional conformal radiation therapy (3D-CRT) and etc. The advantages and disadvantages of each method are compared with each other, as an example from the Slav Yartsev *et al*. (2006), using the 3D-CRT therapeutic method than IMRT in treating patient in lung area has better therapeutic outcomes. Also, study of Murshed *et al.* (2006), shows that the using of IMRT decreases the volume and normal tissue doses in thorax, while the spinal cords dose increased in patients with lung cancer. Therefore, selection of the appropriate therapeutic method and its proper implementation has high importance in radiotherapy. In radiotherapy centers, the dose distributions Planning Target Volumes (PTVs) and critical organs are assessed with different treatment planning systems and the most appropriate technique are selected for each patient. Furthermore, various factors such as type of computation algorithm used in treatment planning system, appropriate selection of field sizes, number of beams, beam's direction and weight and intensity modulators (such as wedge, compensators, etc.) are effective on dose distributions in treatment planning systems. Different treatment planning software's uses different computational algorithms such as ETAR, pencil beam algorithms, Superposition/Convolution Algorithm (SCA) and etc, for photon and electron transport and finally calculation of energy transfer and absorbed dose in different parts of the body.

One of the fundamental challenges in radiation therapy is selection of appropriate energy for performing a proper therapeutic plan and to achieve a high quality health care (Wang *et al.*, 2002). Since the accuracy of computational algorithms are different in high and low energy beams, so that low energy beams have the highest computational precision (Solaiappan *et al.*, 2009; Madani *et al.*, 2007). In addition, the appropriate energy selection for dose calculation depending on the factors such as: tumor depth, homogenous or heterogeneous of tissues, density of tumoral and normal tissues that are on the radiation beam's path. For example, using high-energy radiation in heterogeneous areas with a low density, such as

Corresponding Author: Nasrollah Jabbari, Department of Medical Physics and Imaging, Urmia University of Medical Sciences, Urmia, Iran

thorax, causes loss of lateral dose equilibrium (Wang *et al.*, 2002; Klein *et al*., 1997; White *et al.*, 1996; Ekstrand and Barnes, 1990; Young and Kornelsen, 1983; Kornelsen and Young, 1982).

However, in radiotherapy for tumors in deep, high energy (≥10 MV) and for shallow tumors, intermediate and low energies (≤10 MV) are used (Solaiappan *et al*., 2009; Laughlin *et al*., 1986). As regards, the dose distribution in different depths will liaise to multiple parameters such as homogenous or heterogeneous of tissues, tissue density, "location, size and depth of tumor", depth of photons penetration, the used conventional radiation therapy technique and etc. Soderstrom *et al*. (1999) and Garrison *et al*. (1952). Therefore, selection of the appropriate energy in the desired therapeutic areas, particularly in heterogeneous areas to access a high quality care is important. This subject in rectal and lower esophageal cancers treatment due to tissue heterogeneity in these regions and the high incidence of these cancers is further considered. Since, the rectal cancer is the most current and third cancer after the prostate cancer among men and breast cancer among women (Ferlay *et al*., 2007) and in its radiation therapy a wide volume of pelvis is irradiated. So, protecting the vital organs around the therapeutic area such as bladder and head of femurs in the pelvis region is necessary.

Studies show that using 3D-CRT technique in comparison to conventional radiotherapy has improved the local tumor control and reduces the received dose to the normal tissues such as bladder and spinal cord in radiotherapy of rectum and esophagus (Koelbl *et al*., 2003; Myerson *et al*., 2001; Tait *et al*., 1997).

In addition, the selection of appropriate energy (low or high energies) to treat patients with lung cancer is discussed (Fung, 2003; White *et al*., 1996). In 3D-CRT radiotherapy method, a number of patients with lung cancer under high energies (15-18 MV) to achieve to the uniform coverage dose and more penetration dose and skin dose protection were treated (Wang *et al*., 2002). But in conventional radiotherapy the lower energies are used for treatment of lung tumors (Weiss *et al*., 2007; Blomquist *et al*., 2002; Wang *et al*., 2002; White *et al*., 1996). Therefore, performing the 3D-CRT treatment planning in the thoracic and pelvis areas by using of the photon beams with various energies to assess the dose distribution in tumoral and normal tissues in these regions is necessary. So, the aim of the present study is evaluating the effect of low and high energy photon beams (6-15 MV) on various conformal radiation therapy plans in treating rectal and lower esophageal cancers.

MATERIALS AND METHODS

Patients and equipment: this study has done on 12 patients with lower esophageal cancer (7 male and 5 female) with mean age 61.24±6.83 years and 12 patients with rectal cancer (5 male and 7 female) with mean age 64.62±7.31 years that have been treated in the radiotherapy department Omid hospital of Urmia from April 2011 to May 2012. The CT-scan images of patients with esophageal and rectal cancers provided with slice thicknesses 4mm and 3mm respectively, by spiral CT-scan system (Siemens Company's product, Germany). The CT images from both thorax and pelvis regions were imported to the CorePLAN treatment planning system (Seoul C & J, Seoul, Korea). The treatment planning system by using beam's data of the Siemens linear accelerator machine the PRIMUS model was commissioned.

Contouring: After importing of CT images in to three-dimensional treatment planning system, initially in the lower esophageal and rectal areas on the all slices, the Gross Tumor Volume (GTV) and Clinical Target Volume (CTV) were manually contoured by the oncologist. In addition, in the thoracic region the spinal cord and in the pelvis area the bladder and head of femurs were selected and contoured by the oncologist as Organs at Risk (OARs). To obtain the planning target volumes in the lower esophageal region, the size of margins were considered 1cm in all directions on CTVs. Also to define the PTVs in the rectal regions, aside from its confluence with the bladder (with 0.7 cm margin to the CTV) in other directions a 1cm margin was added isotropically to CTVs. All treatment plans were designed as conformal with 6 and 15 MV energies by using of the CorePLAN three-dimensional treatment planning software. This treatment planning system uses the collapsed cone convolution (CCC) and Equivalent Tissue Air Ratio (ETAR) algorithms for dose calculations (Moradi *et al*., 2012; Jung *et al*., 2012).

Treatment planning: In treating of lower esophageal, 7000 cGy dose in 35 fractions in 7 weeks with 200 cGy daily were administered for conformal treatment planning. We used three coplanar and non-opposed beams with equal weights at angles of zero, 120 and 240°. For the purpose of appropriate dose coverage on the target and protecting the sensitive organs, shaping to the field by using of cerrobend blocks on different fields was done and all fields according to the PTV size were shielded. For treatment of rectal cancers, radiation was delivered at the dose of 5040 cGy in 28 fractions of 180 cGy per fractions, 5 days/week, over 6 weeks. Rectal treatment plan fields were done as a box at angels of zero degree (AP), 90° (Lt. Lat.), 180° (PA) and 270° (Rt. Lat.) with equal weights and the shielding action carried out by using of cerrobend blocks under conditions mentioned above.

The average PTV volumes of the plans in the thoracic area was 119.71 cc (104.4-147.15 cc) and in the pelvis area was 145.38 cc (128.05-178.8 cc). To study the effect of radiation photon beam's energy on dose distributions inside the PTV and eventually on critical organs, in each plan except the incident photon beam energy, all of the other parameters including beam's arrangement, number of beams, weight of beams, the dose prescription, the way of the shielding, etc. were considered similar to each other.

Analytical framework: For the qualitative assessment of performed plans in the studied areas with 6 and 15 MV photon beams, the Dose Volume Histogram (DVH) curves for PTVs and intended critical organs (spinal cord, bladder and head of femurs) were calculated and compared with each other. In order, determining which of the performed plans with two mentioned energies have a better PTV dose distribution on the non-homogenous area, some of the dosimetric parameters (HI, CI, NTID) were also evaluated by using of treatment planning system (TPS's) data. The Homogeneous index (HI) was defined as $D_{5\%}/D_{95\%}$ (dose received by 5% volume of the PTV/ dose received by 95% volume of the PTV) (Chung *et al*., 2011);

$$HI = \frac{D_{5\%}}{D_{95\%}}$$

By selecting the 95% isodose line, the $CI_{95\%}$ was defined (Chung *et al*., 2011):

$$CI = \frac{Volume \quad within \quad 95\% \quad isodose \quad line}{volume \quad of \quad PTV}$$

The closer the CI value is to one, the better the dose conformity (Zhai *et al*., 2012).

The closer the HI and CI values are to 1, we have the better the homogeneity and conformity. We also for knowing which of the plans give a better protection to the sensitive and critical organs; we calculated the integrated dose to normal tissue (NTID) for spinal cord and bladder. The NTID is defined as a volume of the region of interest (ROI) times an average dose;

$$NTID = \text{Volume of ROI (cc)} \times \text{Mean dose (Gy)}$$

In addition to NTID, for OARs D_{10}, D_{30} and D_{50} (D_{10} is dose 10% of the volume of the desired structure) for spinal cord, bladder and head of femurs were calculated.

Statistical analysis: The statistical test (t-test) for statistical analysis of results was used (SPSS software, 16th edition). Differences were considered significant at $p<0.05$.

RESULTS

In this study we compared and evaluated the 3D-CRT plans by using of some dosimetric characteristics and analyzed the therapeutic plans with 6 and 15 MV photon beam energies on 12 patients with rectal cancer and 12 patients with lower esophageal cancer. In Table 1 the mean value and range of changes in the PTV volumes and sensitive organs at risk in the treated areas is shown. In Fig. 1a and 1b the dose distribution of therapeutic plans with 6 MV and 15 MV photons in the lower esophagus area are shown. Also, in Fig. 2a and 2b the dose distribution of therapeutic plans with 6 MV and 15 MV photons in the pelvis area is shown. In addition, the DVH curves for the thoracic area's PTV and the spinal cord as OAR of this area is shown in Fig. 3. This curves for the pelvis area's PTV and bladder and head of femurs as OARs of this area are shown in Fig. 4.

The received dose of different PTV volumes in the thoracic and pelvis areas with two different plans from 6 and 15 MV photon beams is given in Table 2. As evident from Table 2, in the lower esophageal area the difference percentage of average received dose of different volumes of PTV (PTV_5, PTV_{95} and PTV_{100}) in the 6MV vs. 15MV treated plan is between 0.12%-1.88% and this difference percentage of average received dose in rectal area is 0.26% to 0.77%. For all evaluated therapeutic plans in both thoracic and pelvis areas, the difference between two energies is slight and non significant (Table 2). In Table 3, a summary of OAR dosimetric data for all patients used in this study are shown. As can be seen, in the thoracic area the spinal cords mean received dose in the therapeutic plan with 6MV photon than 15MV photon has been reduced. But in the pelvis area, the bladder's and head of femurs mean received doses in the therapeutic plan with 15MV photon than 6MV photon have been reduced.

Table 1: Volumes of the PTVs and OARs of studied patients

Treatment region	PTV Volume (cc) Mean±SD	Bladder (cc) Mean±SD	Spinal cord (cc) Mean±SD	Head of femurs (cc) Mean±SD
Esophagus	119.71±12.57	-	27.71±5.30	-
Rectum	145.38±16.50	259.1±59.43	-	110.84±25.58

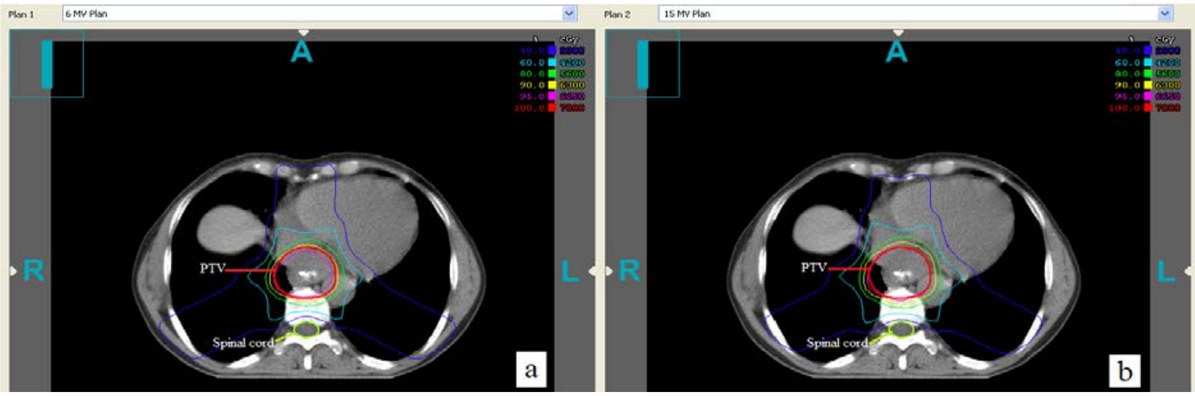

Fig. 1: Dose distribution of therapeutic plans with 6MV (a) and 15MV (b) photons in the lower esophageal region

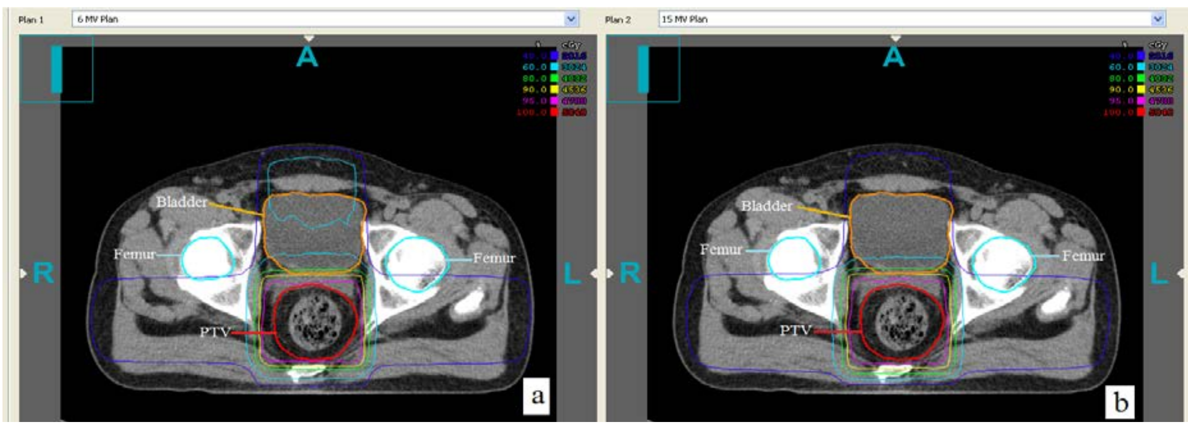

Fig. 2: Dose distribution of therapeutic plans with 6MV (a) and 15MV (b) photons in the rectum area

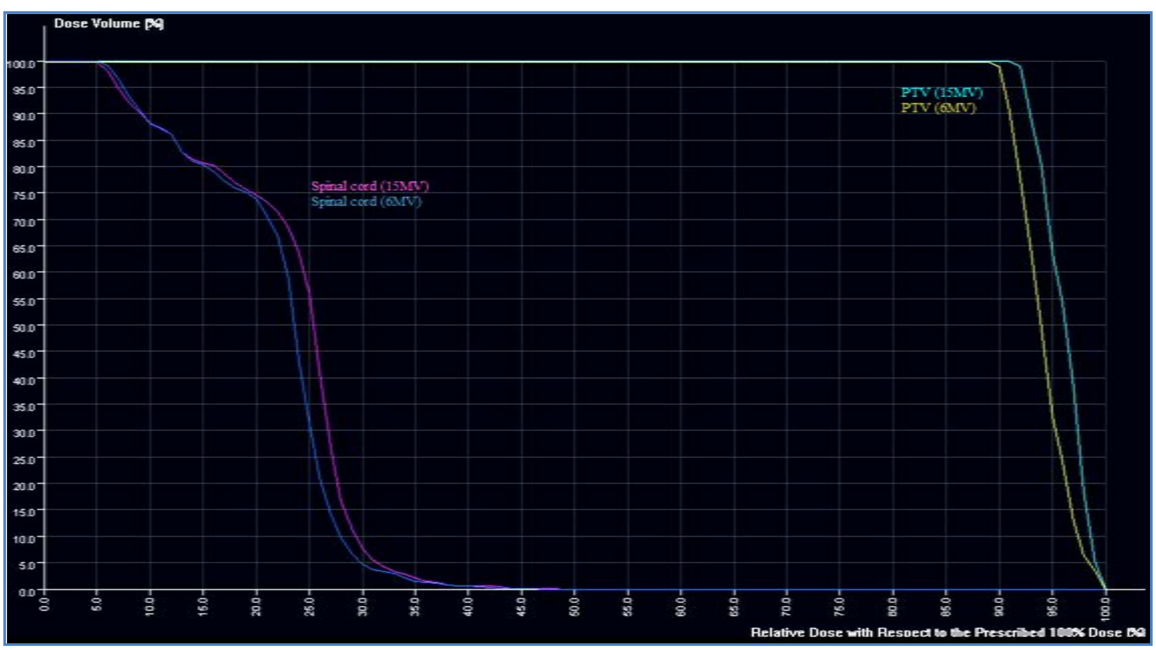

Fig. 3: The DVH curves for the lower esophageal PTV and the spinal cord as OAR of this area

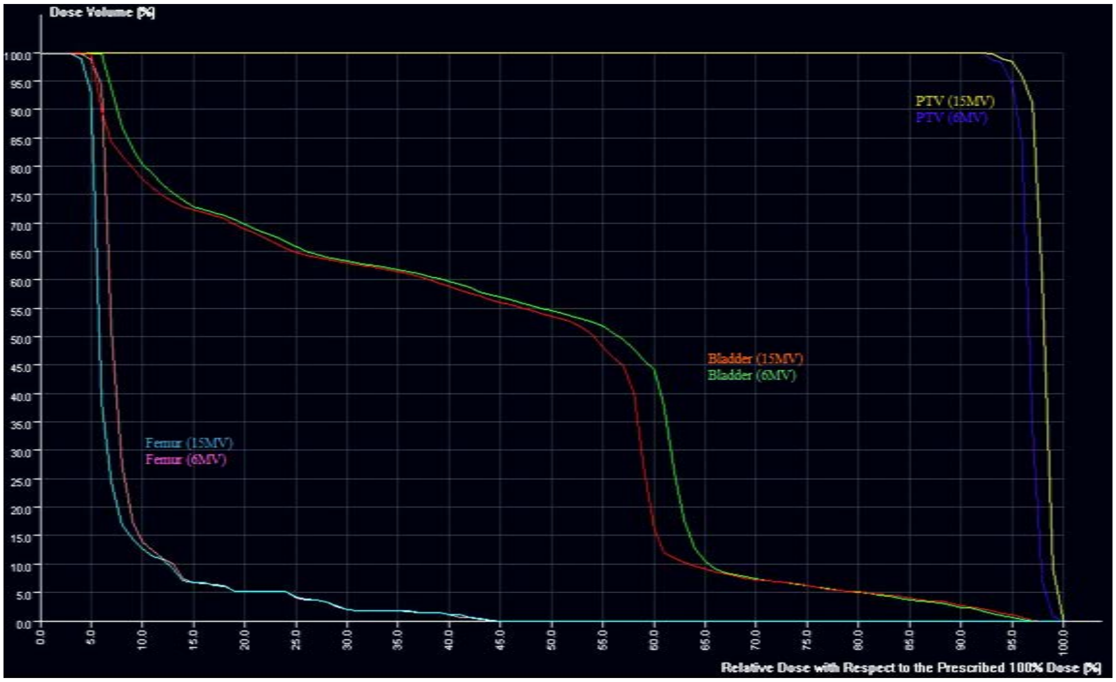

Fig. 4: The DVH curves for the pelvis area's PTV, bladder and head of femurs as OARs of this area

Table 2: 3DCRT plans comparison for the PTV of investigated patients

Region of interest	% of the PTV volume	6-MV plan Mean±SD (cGy)	15-MV plan Mean±SD (cGy)	Difference of MD (6MV vs. 15MV) (%)
Esophagus	D100	5920±279	6010±255	1.52
	D95	6132±240	6247±199	1.88
	D5	6931±30	6939±20	0.12
Rectum	D100	4474±151	4446±128	-0.63
	D95	4672±139	4636±134	-0.77
	D5	4967±95	4954±100	-0.26

MD: mean dose, PTV D100, D95, and D5: dose to 100%, 95%, and 5% of the volume for the PTV

Table 3: Summary of OAR dosimetry data for investigated patients

Region of interest	6-MV plan Mean±SD (cGy)	15-MV plan Mean±SD (cGy)
Spinal cord D10	1854±221	1932±191
Spinal cord D30	1780±202	1853±171
Spinal cord D50	734±199	1817±166
Bladder D10	3364±516	3392±756
Bladder D30	3071±197	2935±222
Bladder D50	2821±249	2680±232
Femurs D10	1542±180	1512±176
Femurs D30	852±164	833±169
Femurs D50	480±159	443±167

D10, D30, and D50: dose to 10%, 30% and 50% of the volume

Homogeneous index data's (HI), Conformality Index (CI) and cumulative dose of Normal Tissue (NTID) for two different therapeutic plans in 6 MV and 15 MV energies in both thoracic and pelvis areas are shown in Table 4, 5 and 6, respectively. In the thoracic the average of HI for 6MV and 15MV plans is 1.13±0.04 and 1.11±0.03, respectively and the CI index is 1.02±0.04 and 1.13±0.05, respectively. Also in the thoracic area the average of NTID for 6MV and 15MV plans is 487.03±70.85 cc-Gy and 512.40±74.27 cc-Gy. We found that in the thoracic area the HI indexes in both different therapeutic plans have a slight difference and the CI index in the therapeutic plan with the 6MV photon is better than the therapeutic plan with 15MV photon.

In the pelvis area the average of HI for 6MV and 15MV plans is 1.08±0.02 and 1.08± 0.02, respectively and the CI index is 1.15±0.02 and 1.01±0.01 respectively. Also in this area the mean NTID index for mentioned plans is 7271.31±1028.51 cc-Gy and 6920.79±1020.52 cc-Gy, respectively. So, we found that in the pelvis area the HI indexes don't diverge in both difference treatment plans but the CI index in 15MV treatment plan than 6MV has a better situation. In addition, it is noted that in this part the NTID in the plan with 15MV photon is averagely 4.90% less than the 6 MV plan.

Table 4: HI, CI and NTID for 6-MV and 15-MV photon plans for 12 patients (Esophagus region)

	HI		CI		NTID (cc-Gy)- spinal cord		
Patient	6-MV	15-MV	6-MV	15-MV	6-MV	15-MV	Difference (%)
1	1.07	1.06	1.01	1.08	485.33	526.42	8.47
2	1.11	1.09	1.01	1.16	575.07	603.57	4.96
3	1.08	1.06	1.01	1.16	486.02	543.62	11.85
4	1.18	1.14	1.03	1.16	644.40	681.11	5.70
5	1.19	1.15	1.01	1.02	535.26	542.60	1.37
6	1.12	1.12	1.01	1.16	478.85	478.85	0.00
7	1.13	1.11	1.02	1.04	506.47	537.53	6.13
8	1.14	1.15	1.14	1.16	415.69	441.81	6.28
9	1.13	1.11	1.01	1.16	481.43	491.78	2.15
10	1.10	1.09	1.01	1.16	388.26	417.78	7.60
11	1.21	1.15	1.01	1.16	391.59	416.61	6.39
12	1.12	1.11	1.02	1.16	456.05	467.20	2.44
Mean ± SD	1.13±0.04	1.11±0.03	1.02±0.04	1.13±0.05	487.03±70.85	512.40±74.27	5.28±3.20

HI: Homogeneity Index (D5/D95), CI: Conformity Index, NTID: Normal Tissue Integrated Doses

Table 5: HI, CI and NTID for 6-MV and 15-MV photon plans for 12 patients (Rectum region)

	HI		CI		NTID (cc-Gy)- bladder		
Patient	6-MV	15-MV	6-MV	15-MV	6-MV	15-MV	Difference (%)
1	1.10	1.11	1.16	1.03	9221.81	8768.77	-4.91
2	1.10	1.10	1.16	1.01	8247.03	7830.64	-5.05
3	1.06	1.06	1.16	1.02	6994.68	6724.51	-3.86
4	1.07	1.08	1.16	1.02	5856.01	5417.85	-7.48
5	1.11	1.05	1.08	1.01	6604.91	6318.70	-4.33
6	1.07	1.07	1.13	1.01	7597.13	7212.72	-5.06
7	1.04	1.06	1.16	1.02	7692.85	7155.54	-6.98
8	1.06	1.05	1.15	1.01	8518.59	8328.40	-2.23
9	1.11	1.11	1.16	1.01	7272.24	6958.70	-4.31
10	1.08	1.09	1.14	1.00	7243.50	6991.75	-3.48
11	1.08	1.10	1.16	1.04	5579.99	5257.12	-5.79
12	1.08	1.08	1.16	1.00	6426.96	6084.78	-5.32
Mean ±SD	1.08±0.02	1.08±0.02	1.15±0.02	1.01±0.01	7271.31±1028.51	6920.79±1020.52	-4.90±1.38

HI: Homogeneity Index (D5/D95), CI: Conformity Index, NTID: Normal Tissue Integrated Doses

Table 6: NTID for 6-MV and 15-MV photon plans for 12 patients (head of femurs)

	NTID (cc-Gy)- head of femurs		
Patient	6-MV	15-MV	Difference (%)
1	639.09	531.06	-16.90
2	612.94	547.70	-10.64
3	490.74	456.54	-6.97
4	551.84	502.12	-9.01
5	529.88	504.00	-4.88
6	475.08	430.63	-9.35
7	376.92	347.40	-7.83
8	674.02	652.62	-3.17
9	261.03	219.33	-15.98
10	467.52	435.98	-6.75
11	739.43	659.59	-10.80
12	603.48	547.78	-9.23
Mean ± SD	535.16±126.88	486.23±117.22	-9.29±3.85

NTID: Normal Tissue Integrated Doses

Table 7: Monitor units comparison for the 6-MV and the 15-MV photon plans of investigated patients

Region of interest	6-MV plan Mean±SD (MU)	15-MV plan Mean±SD (MU)	Difference (%)
Esophagus	295±24	252±15	16.8±3.3
Rectum	289±23	239±12	20.8±3.4

In the thorax area the average of delivered dose of spinal cord for 6 MV and 15 MV plans is 1757.59 cGy and 1849.15 cGy, respectively. Also in the pelvis area the average of delivered dose of bladder for 6 MV and 15 MV plans is 2806.37 cGy and 2671.08 cGy, respectively; and for head of femurs in 6 MV and 15 MV plans is 482.82 cGy and 438.67 cGy, respectively.

Comparison of total MU required for 6MV and 15MV plans in two areas in the rectum and lower esophageal can be seen in Table 7. As it implies the mean required of MU in both areas of lower esophageal and rectal with the 6MV plan is 16.8%±3.4 and 20.8%±3.4 respectively higher than the 15 MV plan.

DISCUSSION

Our study shows that there is no significant difference between 3D-CRT with 6 MV and 15 MV energies in uniform dose coverage PTV in the non-homogene areas of lower esophageal and rectum. In this areas the percentage difference in mean received dose in the 100% of PTV volume with 6 MV energy plan than with 15 MV energy plan is 1.52% and -0.63%, respectively. Percentage differences in mean received dose in the 5% and 95% of PTV volumes in the lower esophageal are less than 2% and in the rectum is less than 1% (Table 2). Our findings adhere with studies done by Solaiappan *et al*. (2009), Yartsev *et al*. (2006), Murshed *et al*. (2006) and Wang *et al*. (2002).

Differences obtained in $CI_{95\%}$ in thoracic and pelvic areas are not significant statistically. These small differences reflect this fact that the dose coverage of targets in the plans with 6 and 15 MV energies is almost equal. Based on the treatment planning system algorithm it can be seen that in the thoracic area the plan with 15 MV is a little better than the plan with 6 MV and in the pelvic area is contrary to the above subject. However, it should also be considered the fact that in the low density areas such as lung the penumbra of 15 MV beam larger than the 6 MV, although the 15MV photon beam has better dose distribution (Madani *et al*., 2007).

Several studies in the thoracic and pelvic areas (Yartsev *et al*., 2006; Murshed *et al*., 2006; Wang *et al*., 2002; Ekstrand and Barnes, 1990; Kornelsen and Young, 1982) have been showed that there is no difference in does distribution for low and high energy photon beams. However, evaluating the dosimetric parameters of DVHs in this study showed that the organs at risk in the thoracic and pelvic regions are better protected in plan with 6 MV than 15 MV.

Another results of our study in this research is that in the lower esophageal area NTID parameter in plan with 6 MV energy is better and less than plan with 15 MV energy and also in the pelvic area NTID index in plan with 6 MV beam than plan with 15MV is higher. So, we can conclude that the selection of proper energy in radiotherapy with photon beams lead to better protect the normal tissues and organs at risk (White *et al*., 1996).

The Table 6 data shows that the required MU in thoracic and pelvic areas with plan 6 MV is about 15%-20% higher than plan with 15 MV. It seems that whatever the beam energy increases the required MU to deliver does to target decreases. However, this energy increment leads to more production of secondary photons and at energies above 10 MV; neutrons will be produced that is radiobiological dangerous (Laughlin *et al*., 1986; Young and Kornelsen, 1983; Klein *et al*., 1997).

CONCLUSION

Our results suggest that using of low energy photon beams in lower esophageal treatment and high energy photon beams in the rectal treatment provides the better dose coverage in the therapeutic plans of lower esophageal and rectal cancers. Finally, with such as therapeutic plans the cumulative dose of organs at risk will be reduced.

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