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ORIGINAL ARTICLE

Evaluating the influence of 6 MV and 15 MV photon beams on prostate intensity-modulated radiation therapy plans

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Abstract

Objective We aimed to determine the effects of low- and high-energy intensity-modulated radiation therapy (IMRT) photon beams on the target volume planning and on the critical organs in the case of prostate cancer.

Methods Thirty plans were generated by using either 6 MV or 15 MV beams separately, and a combination of both 6 and 15 MV beams. All plans were generated by using suitable planning objectives and dose constraints, which were identical across the plans, except the beam energy. The plans were analyzed in terms of their target coverage, conformity, and homogeneity, regardless of the beam energy.

Results The mean percentage values of $V_{70\,Gy}$ for the rectal wall for the plans with 6 MV, 15 MV, and mixed-energy beams were 16.9%, 17.8%, and 16.4%, respectively, while the mean percentage values of $V_{40\,Gy}$ were 53.6%, 52.3%, and 50.4%. The mean dose values to the femoral heads for the 6 MV, 15 MV, and mixed-energy plans were 30.1 Gy, 25.5 Gy, and 25.4 Gy, respectively. The mean integral dose for the 6 MV plans was 10% larger than those for the 15 MV and mixed-energy plans.

Conclusion These preliminary results suggest that mixed-energy IMRT plans may be advantageous with respect to the dosimetric characteristics of low- and high-energy beams. Although the reduction of dose to the organs at risk may not be clinically relevant, in this study, IMRT plans using mixed-energy beams exhibited better OAR sparing and overall higher plan quality for deep-seated tumors.

Key words intensity-modulated radiation therapy (IMRT); mixed-energy plans; 6 MV; 15 MV; prostate cancer; radiation treatment planning; dose-volumetric analysis

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Prostate cancer is a common malignancy. In recent years, there has been an increase in the number of prostate cancer patients treated by using external beam radiotherapy. Three-dimensional conformal radiotherapy (3DCRT) for prostate cancer had commonly been performed by using a "4-field box" technique, with two opposing anterior posterior fields and two opposing lateral fields, until intensity-modulated radiotherapy (IMRT) came into practice. A common practice of 3DCRT for prostate cancer was to treat deep-seated targets by using beams with energies > 10 MV [1]. Since the introduction of IMRT, this technique has been widely used for prostate cancer treatment. Intensity-modulated radiation therapy (IMRT) can be used for delivering conformal dose distributions by varying the radiation intensities within each field according to the intensity maps optimized by using a treatment planning system (TPS). The conformal dose distributions are often stipulated by dose and dose-volume constraints for targets and organs at risk (OARs) [2–3]. By virtue of this capability, IMRT has enabled the delivery of conformal doses to the target while sparing the surrounding normal tissue, which can furthermore enable

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dose escalation that would be beneficial for the outcome of radiotherapy [4–6].

One of the fundamental challenges in the radiation therapy is the selection of an appropriate energy for performing a proper therapeutic plan and for delivering high-quality treatment. Yet, the accuracies of the employed computational algorithms are different for high- and low-energy beams, with low-energy beams yielding the highest computational precision. In addition, selecting the appropriate energy for dose calculation depends on several factors, including the tumor depth, the homogeneity or heterogeneity of tissue, the density of the tumor and normal tissue that is located on the radiation beam's path [7–8].

Setting the appropriate beam energy has been an issue for many therapeutic applications, with 6 MV energy photon beams being more advantageous compared with 60Co gamma rays. For large lesions in the abdomen or pelvis, beams with energies >15 MV are advantageous.

On the other hand, photon beams with the energy of 10 MV or higher yield secondary neutrons owing to the interaction between the beam photons and the machine treatment head [1]. Owing to these secondary neutrons, there is a need to devise methods for avoiding the unnecessary irradiation of patients [9].

The advantages of using low-energy beams include a narrow penumbra, which results in tighter dose distributions around a target, minimizing the irradiation of nearby OARs, negligible neutron contamination, minimizing the head leakage, and internal scatter. However, some research indicates that the regions near the beam entry receive higher doses, and generally, a more complex plan (containing more fields, beam segments, and monitor units [MUs]) is required when using a low-energy beam. This increases the treatment delivery time and the integral dose. Adverse skin reactions are also a concern for low-energy treatment of deep-seated targets, particularly in large-sized patients [1]. Higher energy tends to increase the risk of induction of secondary malignancies owing to a more significant leakage, treatment head scatter, patient scatter, and, in particular, photo-neutron contribution [9–10]. Moreover, high-energy beams exhibit increasingly diffused beam boundaries owing to the long lateral range of secondary electrons. However, literature provides evidence that higher-energy beams provide better dose coverage of the tumor target, while also improving sparing of normal tissue.

However, IMRT is associated with an increase in the number of MUs, treatment time, and amount of leakage relative to the 3DCRT, which has led to concerns related to a potential increase in the risk of acquiring fatal secondary cancers [11–12]. For 6 MV energy 3D-CRT and IMRT prostate treatments, the risk of acquiring secondary cancer has been reported to be in the 0.6%–1.5% and 1%–3.0% range, respectively. For 15 MV energy photon beams, the risk of secondary cancer has been reported to be 3.4% [5]. Therefore, beam energy optimization is an issue of interest and the present study was concerned with the experience of choosing higher-energy beams for achieving more significant penetration depth, while using lower-energy beams for shallower penetration. A fair comparison between the individual low and high beam energy plans and mixed-energy plans was made while keeping the number of beams, the beam arrangement, and the weights of the dose constraints the same across all plans.

Materials and methods

The present study focused on the impact of the photon beam energy on the IMRT of deep-seated tumors. The suitability of using different photon beam energies was evaluated with respect to the treatment site.

The following plan of work was adopted:

(1) Study the performance of the radiotherapy techniques for prostate cancer patients.

(2) Investigate the effects of high- and low-energy photon beams (using beams with the energy of either 6 MV or 15 MV or a combination of these energies) on the quality of IMRT plans for prostate cancer patients.

(3) Evaluate the dose distributions in terms of the target coverage, conformity, and homogeneity, regardless of the beam energy. The rectal wall dose of V_{70Gy} was obtained for the 6 MV, 15 MV, and mixed-energy beams. The mean dose to femoral heads was V_{40Gy} for the 6 MV, 15 MV, and mixed-energy beams. The integral dose for the 6 MV, 15 MV, and mixed-energy beams were also evaluated.

Population of patients

This retrospective planning study included 20 patients treated for localized prostate cancer at the Ayadi Almostakbal Oncology Center, Alexandria, Egypt. All patients underwent a computed tomography (CT) simulation in a supine position. CT images were acquired with the slice thickness of 2 mm. The primary planning target volume (PTVP) was defined with the margin of 2 cm around the prostate and seminal vesicles in all directions, except the posterior and inferior directions, for which the margin of 1 cm was added. The boost PTV (PTVB) was defined with the margin of 1 cm around the prostate in all directions, except the posterior direction, for which the margin of 0.7 cm was added. The rectal wall, the bladder, the femoral heads, and the urethra were contoured as OARs based on the CT images. The bladder and the femoral heads were delineated based on the CT images. The rectal wall was segmented from the level of ischia tuberosities to the recto-sigmoid flexure, according to the protocol of Radiation Therapy Oncology Group (RTOG). In this study, most of our patients underwent the scanning procedure with a full bladder.

Treatment planning

At our center, 6 MV and 15 MV beam energy treatments were delivered on a Siemens (Siemens Medical Solutions, Malvern, PA) ONCOR Expression linear accelerator with an 82 multi-leaf collimator (MLC). IMRT plans were generated retrospectively by using the Xio-CMS treatment planning system (version 4.64.02). The superposition algorithm was used for dose calculations at the grid of 2.5 mm. The total prescription dose was 81 Gy with the daily dose of 1.8 Gy. All patients were treated by using 6 MV beam energy plans, following which we retrospectively created, for each patient, 15 MV beam energy step and shoot IMRT plans that were used for study purposes only and were created according to the hospital research protocol. To ensure that the similarity or difference between the studied plans was due to the energy only, the same optimization constraints were applied to all energy plans, with other parameters (such as the beam angle and the number of beams) kept constant. The dose prescribed for the primary plans was 50.4 Gy, while the dose for the boost plans was 30.6 Gy. For all patients, both the boost (PTVB) and the primary (PTVP) plans were generated by using either 6 MV or 15 MV energy beams alone and by using mixed-energy beams.

The PTV plan goals were set at 95% for the dose prescribed, which covered at least 95% of the PTV, and the PTV volume receiving >104% of the prescription was limited to zero. As the optimization algorithm could not satisfy all of the demands placed on the plans, and segmentation degraded the plans, it was necessary to apply more stringent dose limits to the real planning process than those described [13–15]. For the qualitative assessment of plans in the present study, the constraint on $D_{100\%}$ was set to receive 99.5% of the prescription and the constraint on the maximal dose (D max) was set to receive 102% of the prescription in the optimization process for the primary plans. In the case of the boost plans, the constraint on $D_{100\%}$ was set to receive 102% of the prescription and the constraint on the maximal dose (D max) was set to receive 103% of the prescription in the optimization process. The initial optimization constraints are summarized in Tables 1 and 2. To avoid hot spots in the normal tissue and to obtain sharp dose gradients around the PTVs, the normal tissue objectives were used.

Table 1 The initial dose-volume constraints for the primary plan

Structure	The initial dose-volume constraint
PTV_P[a]	$D_{100\%}$[b] ≥ 99.5% of prescription dose
	$D_{98\%}$ ≥ 100% of prescription dose
	$D_{2\%}$ ≤ 101% of prescription dose
	$D_{max\%}$[c] ≤ 102% of prescription dose
Rectal Wall	V_{50Gy}[d] ≤ 0%
	V_{44Gy} ≤ 20%
	V_{41Gy} ≤ 25%
	V_{30Gy} ≤ 50%
Bladder	V_{50Gy} ≤ 0%
	V_{44Gy} ≤ 30%
	V_{41Gy} ≤ 40%
	V_{30Gy} ≤ 55%
Femoral Heads	V_{34Gy} ≤ 0%
	V_{30Gy} ≤ 10%
	V_{23Gy} ≤ 50%
Body	D_{max}% ≤51.4 Gy

[a] PTV_P denotes the primary planning target volume; [b] $D_{n\%}$ denotes the dose received by the n% volume of the target volume; [c] D_{max}% denotes the maximal received dose; [d] V_{nGy} denotes the percentage volume irradiated by nGY

Table 2 The initial dose-volume constraints for the boost plan

Structure	The initial dose-volume constraint
PTVBa	$D_{100\%}$[b] ≥ 102% of prescription dose
	$D_{98\%}$ ≥ 102.2% of prescription dose
	$D_{2\%}$ ≤ 102.8% of prescription dose
	$D_{max\%}$[c] ≤ 103% of prescription dose
Rectal Wall	V_{30Gy}[d] ≤ 0%
	V_{26Gy} ≤ 20%
	V_{19Gy} ≤ 50%
Bladder	V_{30Gy} ≤ 0%
	V_{26Gy} ≤ 30%
	V_{19Gy} ≤ 55%
Femoral Heads	V_{16Gy} ≤ 0%
	V_{15Gy} ≤ 20%
	V_{12Gy} ≤ 50%
Body	D_{max}% ≤ 31.5 Gy

[a] PTV_B denotes the boost planning target volume; [b] D_n% denotes the dose received by the n% volume of the target volume; [c] D_{max}% denotes the maximal received dose, [d] V_{nGy} denotes the percentage volume irradiated by nGY of a certain structure

Using eight coplanar and non-opposed beams at the gantry angles of 160°, 100°, 60°, 40°, 320°, 300°, 260°, and 200°, the primary plan (PTVP) doses were delivered. For the boost plan, eight coplanar beams were used at the gantry angles of 165°, 95°, 65°, 30°, 330°, 295°, 265°, and 195°. In the case of the mixed beam energy primary plan, 15 MV photon beams at the gantry angles of 100°, 60°, 300°, and 260° were used because these yielded the longest penetration paths, while for the 6 MV beams the rest of the gantry angles were used. In the case of the mixed beam energy boost plan, 15 MV photon beams at the gantry angles of 95°, 65°, 295°, and 265° were used, while 6 MV beams were used for the remaining gantry angles, allowing to use 15 MV photon beams for the gantry angles yielding the deepest penetration. Both high- and low-energy photon beams were present in equal proportions

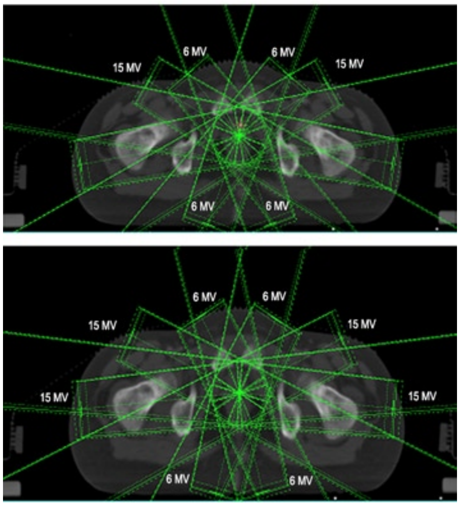

Fig. 1 Beam orientation. (a) The primary mixed-energy plan (with 6 MV and 15 MV energy photon beams); (b) The mixed-energy boost plan (with 6 MV and 15 MV energy photon beams)

in all mixed-energy plans. This was shown in Fig. 1. The intensity map for each beam was generated at the end of the IMRT optimization. All of the IMRT plans were normalized such that 95% of the prescription dose covered at least 95% of the PTV after the optimization process. The primary and boost plans were combined to obtain one plan. The planning was done by a dedicated medical physicist and the clinical aspects were reviewed by a dedicated radiation oncologist.

Dose-volumetric analysis

Dose-volumetric analysis was performed by using DVHs of the treatment plans of individual patients. The homogeneity index (HI) and the conformity index (CI) were calculated for the PTV_P and PTV_B from the primary and the boost plans, respectively. The HI captures the dose homogeneity within the PTV. The HI was calculated as I_{max}/RI, where I_{max} is the maximal isodose in the PTV. The CI was calculated as (volume within the 98% isodose)/(volume of the PTV). The values of CI or HI close to unity indicate greater conformity or homogeneity. We calculated the integrated dose delivered to the normal tissue (NTID). The NTID was calculated manually and was defined as a mean dose multiplied by the structure's volume, yielding NTID = mean dose (Gy) × volume (cc).

The maximal and mean doses to the PTV_P and PTV_B were calculated from the primary, boost, and sum plans. To evaluate the irradiated volumes of the rectal wall and bladder, the volumes that received 70 Gy, 66.6 Gy, 50 Gy, 40 Gy, and 20 Gy (V_{70Gy}, $V_{66.6Gy}$, V_{50Gy}, V_{40Gy}, and V_{20Gy}) were calculated from the sum plans. The mean dose and $D_{50\%}$ were calculated from the sum plans. For the femoral heads, the maximal and mean doses V_{50Gy}, V_{45Gy}, V_{30Gy}, and $D_{50\%}$ were calculated from the sum plans. For the body, $V_{24.5Gy}$ (cc) was calculated from the sum plans to evaluate the volume that received –30% of the prescription dose. The mean doses, D_{mean} of the bladder, the rectum, and the femoral heads, for the primary and boost plans, were compared separately, too. The mean DVHs for each OAR were also generated from the individual DVHs. Data analysis was performed by using a paired *t*-test to determine dose-volumetric differences for 6 MV vs. 15 MV plans, 6 MV and mixed-energy plans, and 15 MV and mixed-energy plans. Differences were considered statistically significant at $P \leq 0.05$.

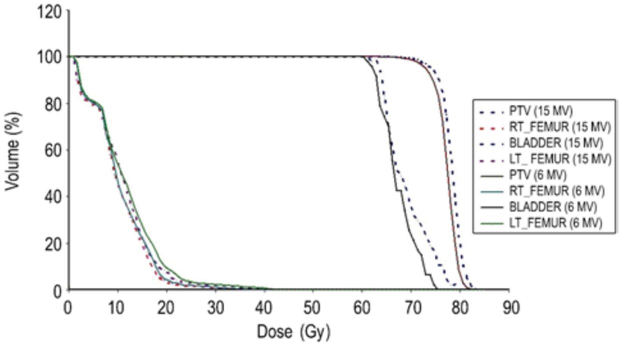

Fig. 2 Comparison of dose volume histograms (DVHs) for the case of prostate. The solid lines indicate DVHs for the IMRT with the 6 MV plan. The dashed lines indicate the DVHs for the 6 MV plan

Results

Conformity and homogeneity of the target

A quantitative analysis was conducted for comparing the results. There were clear differences in the homogeneity index between the 6 MV and 15 MV primary plans, and no difference between the 6 MV and mixed-energy primary plans (1.05 vs. 1.09 for CI and 1.046 vs. 1.06 for HI, $P = 0.016$ and $P < 0.001$). The quantitative analysis for the boost plans with the 6 MV and 15 MV energy beams yielded the target dose conformity and homogeneity values of 1.04 vs. 1.03 (for CI) and 1.04 vs. 1.05 (for HI), with $P = 0.028$ and $P < 0.001$, respectively. For the boost plan with the mixed-energy beam the target dose homogeneity was the same as that for the 6 MV beam energy plan (1.05 vs. 1.05). The boost plan with the mixed-energy beam yielded slightly better target dose homogeneity than the 6 MV beam energy plan (with 1.04 vs. 1.05 for the boost plan, $P = 0.5$ and $P < 0.001$, respectively). Both the primary and the boost plans with the mixed-energy beam yielded slightly better target dose conformity values than the plans with the 15 MV beam (1.05 vs. 1.09 for the primary plans and 1.03 vs. 1.35 for the boost plans, $P < 0.001$ and $P = 0.003$, respectively). There was no clear difference between the homogeneity indices of the 15 MV and mixed-energy plans.

Maximal and mean dose to target

A quantitative analysis was performed and no clear differences were observed among the 6 MV, 15 MV, and mixed-energy plans. The maximal dose to the $\mathrm{PTV_P}$ for the 6 MV beam energy sum plan was slightly lower than the values obtained for the other two plans, yet not reaching statistical significance. Statistically significant differences were observed between the maximal and mean doses to the PTVP for the primary plans with the 15 MV and mixed-energy beams (51.23 Gy vs. 52.47 Gy, with $P < 0.001$; and 49.33 Gy vs. 50.31 Gy, with $P < 0.001$). Weakly statistically significant differences were observed between the maximal and mean doses to the $\mathrm{PTV_B}$ for the boost plans with the 15 MV and mixed-energy beams. The mean dose to the $\mathrm{PTV_B}$ was slightly higher for the mixed-energy sum plan compared with the 15 MV beam energy sum plan, but the difference was below 1% of the prescription dose (81.68 Gy vs. 81.23 Gy, $P < 0.001$).

Comparisons for the OARs dose to the rectal wall

The rectal wall volumes for the 6 MV plans that received 40 Gy (V40 Gy) were larger than those for the 15 MV plans. The rectal wall volumes for the 15 MV plans that received 70 Gy and 66.6 Gy were larger than those for the 6 MV plans (17.8% vs. 16.9% for $V_{70\,\mathrm{Gy}}$ and 21.1% vs. 19.7% for $V_{66.6\,\mathrm{Gy}}$, $P = 0.002$ and $P = 0.002$, respectively). The mean value of $V_{20\,\mathrm{Gy}}$ for the 15 MV plans was smaller than that for the 6 MV plans (81.5% vs. 90.4% for $V_{20\,\mathrm{Gy}}$, $P = 0.001$). For all dose volume parameters, the differences were not statistically significant, except for $D_{50\%}$ and $V_{40\,\mathrm{Gy}}$ ($P < 0.02$, $P < 0.01$ respectively) (Table 3). The mixed-energy plans always exhibited a lower dose to the rectal wall compared with the 6 MV and 15 MV plans. The differences for $V_{70\mathrm{Gy}}$, $V_{66.6\mathrm{Gy}}$, and $V_{50\mathrm{Gy}}$ between the 6 MV and mixed-energy plans were relatively small, and for $V_{70\mathrm{Gy}}$ and $V_{66.6\mathrm{Gy}}$ no statistical significance was reached. However, the differences for $V_{40\mathrm{Gy}}$ and $V_{20\mathrm{Gy}}$ were relatively large and reached statistical significance (53.6% vs. 50.4% for $V_{40\mathrm{Gy}}$ and 90.38% vs. 80.4% for $V_{20\mathrm{Gy}}$, $P < 0.001$ and $P < 0.001$, respectively). The mean doses and the D50% values were larger for the 6 MV and 15 MV plans compared with the mixed-energy plan, reaching statistical significance (46.84 Gy for the 6 MV plan and 45.84 Gy for the 15 MV plan vs. 44.27 Gy for the mixed-energy plan for the mean dose, and 43.15 Gy for the 6 MV plan and 42.88 Gy for the 15 MV plan vs. 40.68 Gy for the mixed-energy plan for the D50% value).

Dose to the bladder

For the bladder, the volumes receiving ≥ 66.6, 50, 40, 20 Gy and the mean, $D_{50\%}$ were smaller for the 15 MV plans compared with the 6 MV plans. The doses to the bladder for the 15 MV plans were always slightly higher than those for the 6 MV plans. The mean $D_{50\%}$ for the 6 MV plans was lower than that for the 15 MV plans (35.12 Gy vs. 37.5 Gy, $P = 0.003$). The doses to the bladder for the mixed-energy plans were always slightly lower than those for the 15 MV plans, reaching statistical significance, even though the differences were not large. The doses to the bladder for the mixed-energy plans were always slightly higher than that those for the 6 MV plans. However, the differences were negligible and did not reach statistical significance.

Dose to the femoral heads

Although the mean, the $V_{30\,\mathrm{Gy}}$, and the $D_{50\%}$ doses for the 6 MV plans were higher than those for the 15 MV, no significant differences between the dose-volume parameters were found for the 6 MV and 15 MV plans. The doses to the femoral heads for the 6 MV plans were always higher than those for the 15 MV and mixed-energy plans, with statistically significant differences. The mean dose was 30.1 Gy for the 6 MV plans, 25.5 Gy for the 15 MV plans ($P < 0.001$ for comparing the 6 MV plan result with the 15 MV plan result), and 24.4 for the mixed-energy plans ($P < 0.001$ for comparing the 6 MV plan result with the mixed-energy plan result). The $D_{50\%}$ value was 31.4 Gy for the 6 MV plans, 25.86 Gy for the 15 MV plans ($P < 0.001$ for comparing the 6 MV plan result with the 15 MV result), and 25.86 Gy for the mixed-energy plans ($P < 0.001$ for comparing the 6 MV plan result with the mixed-energy plan result). The doses to the femoral heads for the 15 MV plans were always higher than those for the mixed-energy plans. However, the differences were not statistically significant, except for $V_{45\,\mathrm{Gy}}$ ($P = 0.01$). The mean doses and the $D_{50\%}$ values for the 15 MV and mixed-energy plans were similar, and the differences were not statistically significant.

Dose to the normal tissue and the number of monitor units

The body volume that received 30% of the prescription dose was reduced to 1696 cc and 2188 cc for the 15 MV and mixed-energy plans, respectively, compared with the value of 2693 cc for the 6 MV plans ($P < 0.001$ for comparing the 6 MV plan results with the 15 MV plan results, and $P \leq 0.04$ for comparing the 6 MV plan results with the mixed-energy plan results). Integral doses for the 6 MV, 15 MV, and mixed-energy plans were 121 000 Gy-cc, 110 000 Gy-cc, and 110 000 Gy-cc, respectively. The mean number of monitor unit for the mixed-energy plans was higher than those for the 15 MV and 6 MV plans, yet did not reach statistical significance (1050 MUs for the 6 MV plans, 912 MUs for the 15 MV plans, and 1061 MUs for the mixed-energy plans).

Table 3 The dose-volumetric analysis results for all plans (6 MV, 15 MV and mixed-energy IMRT)

Variables	6 MV IMRT	15 MV IMRT	Mixed-energy IMRT	*P* value (6 vs.15)[a]	*P* value (6 vs. mixed)[b]	*P* value (15 vs. mixed)[c]
Primary plan (mean ± standard deviation)						
Conformity index	1.050 ± 0.040	1.09 ± 0.04	1.05 ± 0.02	0.016	0.5	< 0.001
Homogeneity index	1.046 ± 0.010	1.06 ± 0.01	1.06 ± 0.01	< 0.001	< 0.001	0.13
Max. dose to PTVp (Gy)[d]	51.58 ± 0.600	51.23 ± 0.70	52.47 ± 0.79	0.133	0.02	< 0.001
Mean dose to PTVp (Gy)	49.31 ± 0.750	49.33 ± 0.86	50.31 ± 0.50	0.79	< 0.001	< 0.001
Mean dose to rectal wall (Gy)	33.19 ± 0.800	32.47 ± 0.66	32.3 ± 0.54	0.047	0.02	0.185
Mean dose to bladder (Gy)	29.66 ± 1.010	30.51 ± 0.94	29.54 ± 0.80	0.07	0.178	0.001
Mean dose to femoral heads (Gy)	22.86 ± 1.310	20.25 ± 1.87	19.5 ± 1.97	< 0.001	< 0.001	0.54
Boost plan (mean ± standard deviation)						
Conformity index	1.0380 ± 0.005	1.031 ± 0.01	1.033 ± 0.015	0.028	0.15	0.003
Homogeneity index	1.0499 ± 0.005	1.054 ± 0.05	1.059 ± 0.0893	< 0.001	< 0.001	0.15
Max. dose to PTV_B (Gy)[e]	31.490 ± 0.160	31.6 ± 0.19	31.79 ± 0.23	0.0345	< 0.001	0.023
Mean dose to PTV_B (Gy)	30.200 ± 0.210	30.4 ± 0.24	30.55 ± 0.22	0.02	< 0.001	0.043
Mean dose to rectal wall (Gy)	12.950 ± 0.530	12.676 ± 0.53	12.29 ± 0.55	0.102	< 0.001	0.032
Mean dose to bladder (Gy)	12.270 ± 0.400	12.57 ± 0.46	11.97 ± 0.35	0.035	0.02	< 0.001
Mean dose to femoral heads (Gy)	9.50 ± 0.350	8.5 ± 0.62	8.8 ± 0.62	< 0.001	< 0.001	0.0989
Sum plan (mean ± standard deviation)						
Max. dose (Gy)	82.66 ± 0.550	83 ± 0.70	83.34 ± 0.65	0.2	0.009	0.19
Mean dose to PTV_p (Gy)	73.57 ± 0.230	74.63 ± 0.26	74.52 ± 0.27	< 0.001	< 0.001	0.375
Mean dose to PTV_B (Gy)	79.49 ± 0.300	81.23 ± 0.10	81.68 ± 0.12	< 0.001	< 0.001	< 0.001
Mean dose to rectal wall (Gy)	46.84 ± 1.490	45.84 ± 1.30	44.27 ± 1.53	0.052	< 0.001	0.012
V_{70Gy}[f] of rectal wall %	16.90 ± 1.200	17.8 ± 1.00	16.4 ± 1.35	0.002	0.5	< 0.001
$V_{66.6Gy}$ of rectal wall %	19.70 ± 1.200	21.1 ± 1.35	19.16 ± 1.26	0.002	0.3	< 0.001
V_{50Gy} of rectal wall %	38.80 ± 1.390	39.73 ± 1.50	37.8 ± 1.51	0.012	0.03	< 0.001
V_{40Gy} of rectal wall %	53.60 ± 1.300	52.3 ± 2.00	50.4 ± 1.30	0.11	< 0.001	< 0.001
V_{20Gy} of rectal wall %	90.38 ± 8.400	81.5 ± 7.80	80.99 ± 7.60	0.001	< 0.001	0.835
$D_{50\%}$ gof rectal wall Gy	43.15 ± 1.600	42.88 ± 1.60	40.68 ± 1.20	0.609	< 0.001	< 0.001
Mean dose to bladder (Gy)	38.4 ± 1.100	40.16 ± 1.20	38.6 ± 1.10	< 0.001	0.5	< 0.001
V_{70Gy} of bladder %	19.6 ± 1.300	21.69 ± 1.19	20.45 ± 1.24	< 0.001	0.07	0.002
$V_{66.6Gy}$ of bladder%	23.42 ± 0.980	24.4 ± 0.80	23.62 ± 0.78	0.001	0.5	0.001
V_{50Gy} of bladder %	39.7 ± 1.170	41.55 ± 1.70	39.9 ± 1.27	< 0.001	0.5	0.001
V_{40Gy} of bladder %	47.43 ± 1.000	47.52 ± 1.01	47.525 ± 1.05	0.778	0.769	0.98
V_{20Gy} of bladder %	65.6 ± 2.500	65.95 ± 2.40	64.1 ± 2.67	0.6	0.07	0.02
$D_{50\%}$ of bladder cGy	35.12 ± 2.590	37.52 ± 2.18	35.37 ± 2.70	0.003	0.7	0.008
Max. dose to femoral heads (Gy)	48.9 ± 1.300	46.52 ± 0.90	46.025 ± 1.80	< 0.001	< 0.001	0.3
Mean dose to femoral heads (Gy)	30.1 ± 3.100	25.5 ± 1.67	24.4 ± 1.77	< 0.001	< 0.001	0.848
V_{50Gy} of femoral heads %	0.3 ± 0.670	0.005 ± 0.01	.0025 ± 0.01	0.033	0.031	0.519
V_{45Gy} of femoral heads %	6.26 ± 2.570	2.734 ± 2.10	1.1 ± 1.60	< 0.001	< 0.001	0.01
V_{30Gy} of femoral heads %	53.8 ± 10.700	31.32 ± 8.90	30.84 ± 8.95	< 0.001	< 0.001	0.866
$D_{50\%}$ of femoral heads Gy	31.4 ± 4.390	25.86 ± 4.60	25.86 ± 4.20	< 0.001	< 0.001	0.998
$V_{24.3Gy}$ of body (cc)	2693 ± 736.0	1696 ± 726	2188 ± 771	< 0.001	0.04	0.044
Integral dose (10^5 Gy-CC)	1.21 ± 0.100	1.10 ± 0.167	1.10 ± 0.162	0.02	0.01	0.96
Average MU[h]	1050 ± 108.70	912.23 ± 70.806	1061 ± 115.51	< 0.001	0.764	< 0.001
Modulation Factor	2.92 ± 0.300	2.53 ± 0.200	2.95 ± 0.32	< 0.001	769	< 0.001

[a] *P* value (6 vs. 15) denotes the P value for comparing the results of 6 MV IMRT and 15 MV IMRT plans; [b] *P* value (6 vs. mixed) denotes the *P* value for comparing the results of 6 MV IMRT and mixed-energy IMRT plans; [c] *P* value (15 vs. mixed) denotes the P value for comparing the results of 15 MV IMRT and mixed-energy IMRT plans; [d] PTVP denotes the primary planning target volume; [e] PTVB denotes the boost planning target volume; [f] VnGy denotes the percentage volume irradiated by n GY; [g] Dn% denotes the dose received by the n% volume of the target volume; [h] MU is the monitoring unit; A *P* value <.05 is considered as significant

Mean dose-volume histograms

The mean DVHs for the primary and boost PTVs from the sum plans for the 6 MV, 15 MV, and mixed-energy beams are shown in Fig. 2. Dose volume histograms (DVHs) were compared for the case of prostate. The solid lines indicate the DVH values for the IMRT with the 6

MV energy beam. The dashed lines indicate the DVH values for the 15 MV plan femoral heads shows that IMRT.

Discussion

In general, results of the comparison presented above revealed that the difference between the 6 MV and 15 MV plan groups is insignificant. In practice, for achieving the same target coverage, conformity, and homogeneity values, much tighter constraints should be imposed on low-energy treatment plans. No distinctive clinical dosimetric quality differences were found between the 6 MV and 15 MV plans in the present study, in agreement with the results reported in previous studies [14, 16–17]. To maintain the same levels of target coverage, conformity, and homogeneity, the 6 MV plans spared more rectal walls in high-dose regions compared with the 15 MV plans, while the 15 MV plans spared more rectal walls in low-dose regions compared with the 6 MV plans, even though both results were clinically acceptable. This result was explained by the fact that low-energy photon beams can generate tighter dose distributions around a target, and high-energy photon beams provide better penetrating power. The higher femoral head doses observed for the 6 MV plans, compared with those observed for the 15 MV plans, can be understood in the same context. As the femoral heads are located relatively far away from the prostate, they received higher doses when using the 6 MV beams compared with using the 15 MV beams, owing to the penetrating power differences. For the same reason, the values of the volume irradiated with low dose and the integral dose for the 6 MV plans were larger than those for the 15 MV plans. The number of MUs for the 6 MV plans was, on average, 1.1-fold larger than that for the 15 MV plans. Previous research suggested that using low-energy beams in IMRT is more advantageous that using high-energy ones. However, in the case of the 15 MV beams, the situation was different, because photons in 15 MV beams have threshold energy for inducing fatal secondary cancer.

Previously, it was demonstrated that the choice of energy does not sensitively affect the IMRT plan quality for prostate cancer when a sufficient number of fields are used, even for exceptionally large patients [10–11, 17]. Those studies were focused on the cases in which the OAR dose was 50% above the prescription dose. In the present study, we showed that using high-energy beams in prostate IMRT was beneficial for sparing some OARs, even in low-dose regions receiving less than 50% of the prescription dose. Yet, there is a trade-off associated with losing the treatment benefits for high-dose regions, although it is not clinically significant.

Thangavelu *et al* [13] note that the slight advantage of using 15 MV beams associated with better sparing of healthy tissue and better coverage cannot be considered to outweigh the well-known risk of non-negligible neutron production when using these beams. Sun and Ma [14] investigated the feasibility of using 6 MV energy intensity-modulated photons for treating exceptionally large patients with prostate cancer. The study shows that using a 6 MV energy beam is an effective option for treating even very large patients with prostate cancer. Welsh *et al* [15] discussed the theoretical ground for the use of high- and low-energy photons as a comparison between disadvantages and advantages, but the lack of data resulted in a debate about the study conclusions. A few studies have demonstrated that the absolute lifetime risk of fatal secondary malignancy due to IMRT with 15 MV energy photon beams, including the neutron dose, increases slightly compared with that of IMRT with 6 MV energy photon beams (3.4% of lifetime risk for 15 MV IMRT plans and 2.9% for 6 MV IMRT plans) [14, 17–20]. However, the fraction of high-energy photon beams in mixed-energy plans was 50% in this study. A simple arithmetic estimation of the secondary cancer risk from neutrons by using mixed-energy photon beams results in half of the risk when using 15 MV energy photon beams alone. The dose to the normal tissue surrounding the target volume was found to be higher for the 6 MV beams compared with the 15 MV beams, but it should be taken into consideration that for the 6 MV beams there are no secondary neutrons and radiation leakage is relatively low. In addition, room shielding requirements are significantly weaker for 6 MV energy photons than for 15 MV energy photons.

On the other hand, there are concerns related to a wide lateral fall-off of high-energy photon beams owing to a long lateral range of secondary electrons. This can adversely affect the aimed delivery of modulated beams [16, 21–25]. This characteristic of high-energy photon beams degrades saving OARs that are located close to the target, such as the rectum and bladder. Our findings agree with the conclusions of the above-mentioned previously performed studies. However, in the mixed-energy plans, the rectal wall received consistently lower doses. Furthermore, the integral doses for the mixed-energy plans were reduced to, on average, 93% of those for the 6 MV plans. This would be beneficial for reducing the secondary malignancy risks induced by radiotherapy [26].

Conclusion

The 15 MV energy dose distributions and DVHs for the PTV, generated by using clinical treatment planning calculations, were as good as, or slightly better than, those generated by using the 6 MV energy beams. The organs at risk, such as the rectum, the bladder, and the femoral head, were also similar, with the DVH curve for the 6 MV plan being slightly higher near the low-dose region, but lower near the high-dose region. The results of this study indicate that an IMRT plan with a mixed-energy photon beam can be advantageous compared with both low- and high-energy photon beams. Even though the dose reduction to OARs and normal tissue may not be clinically relevant, it is worthwhile to note that using mixed-energy beams in an IMRT plan for treating a deep-seated tumor (such as prostate cancer) can improve the overall plan quality.

Conflicts of interest

The authors indicated no potential conflicts of interest.

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