Influence of photon beam energy on IMRT plan quality for radiotherapy of prostate cancer

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SUMMARY

BACKGROUND: Intensity-modulated radiation therapy (IMRT) has been widely used for prostate cancer treatments. 6MV photon beams were found to be an effective energy choice for most IMRT cases. The use of high-energy photons raise concerns about increased leakage and secondary neutron dose for the patients.

AIM: In this work, the effect of beam energy on the quality of IMRT plans for prostate radiotherapy was systematically studied for competing IMRT plans optimized for delivery with either 6 or 10MV beams.

MATERIALS AND METHODS: A cohort of 20 prostate cases was selected for this study. All patients received full-course IMRT treatments to a dose of 79.2Gy to PTV in 44 fractions. For all of the cases we developed treatment plans using 6 MV and 10MV intensity-modulated beams with identical dose volume constraints.

RESULTS: Percentage of doses received by the percentage volume of PTV was higher for 6MV photons compared to 10MV photons for 12 patients, less than or equal to 1% for 6 patients and 2.6%, 3.6% for the remaining 2 patients irrespective of the PTV volume. Percentage doses received by 15% of bladder volume were higher for 10 MV photons. Percentage doses received by 15% of rectum volume were also higher for 10 MV photons.

CONCLUSIONS: Since there is no greater advantage from 10MV photons as compared with 6MV photons in large volume pelvic IMRT dosimetry and also 10MV photons lie on the threshold energy border for the induction of photo neutrons from the accelerator components, we recommend the use of 6MV photons for IMRT of prostate cancer to achieve better results in tumour control and acceptable probability of complication rate.

KEY WORDS: IMRT, prostate, radiotherapy

BACKGROUND

A standard principle in radiation therapy has been that the deeper the target, the higher the energy that should be used. As is known from the literature, energies ≥ 10 MV are to be preferred for deep-seated pelvic/abdominal lesions, particularly for larger target volumes or larger size patients [1], due to a decrease in the integral dose. In addition, it has been shown that dose deposition near and distant from the target is different for different energies. Low energy produces tighter dose distributions around the target than higher energies, but also deposits a higher dose in the surface region near the beam entry [1, 2].

In contrast, one of the implied tenets of intensity-modulated radiation therapy (IMRT) has been that energy does not matter [3] or is less important [4]. This thesis was originally examined and shown to be the case for rotational IMRT (TomoTherapy), based on the equivalence of mean dose to target and sensitive structures at different energies [3]. In fact, although it has been suggested by Soderstrom et al. that there is still a value to higher energies for deep seated targets as the volume of the target increases [4], the results on rotational delivery have been used by accelerator manufacturers to guide the development of IMRT-dedicated single energy machines using 6 or 10 MV photon beam energies.

Intensity-modulated radiation therapy (IMRT) has been widely used for prostate cancer treatment [5–19]. In practice, high-energy photons such as 18 MV are often used, given the experience of 3D conformal radiation therapy with static beams. However, in IMRT treatments, the effects of the intensity modulation and the use of a relatively large number of beams have been found to reduce the dependence of the treatment planning on the selection of beam energies [20]. As a result, 6-MV photon beams have been found to be an effective energy choice for most IMRT cases [4,21].

In addition, the total monitor units are typically two to three times higher in IMRT than in conventional radiation therapy. Therefore, the use of high-energy photons also raised concerns about increased leakage and secondary neutron dose for the patients [22-24]. However, it is unclear whether low-energy intensity-modulated photons can be used for large-pelvis irradiations because of the low penetration power of the beam.

AIM

In this work, the effect of beam energy on the quality of IMRT plans for prostate radiotherapy was systematically studied for competing IMRT plans optimized for delivery with either 6 or 10 MV beams. To ensure that differences among plans are due only to energy selection, the beam arrangement, number of beams, and dose constraints were kept constant for all plans.

MATERIALS AND METHODS

A cohort of 20 prostate cases was selected for our study. The patient characteristics are given in Table I. The mean anterior-posterior (AP) separation of these patients was 23.3 cm (range 18–30 cm, SD 3.1) and the mean lateral separation was 37.7 cm (range 34–40 cm, SD 2.00). The prostate volume varied from 16.8 to 181.9 cc (mean 69.2 cc, SD 41.4). The planning target volume (PTV) was defined as the entire prostate without seminal vesicles and included a 3 mm margin around the prostate for set-up error. The average PTV for these patients was 123.7 cc (range 38.9–270.9 cc, SD 57.5). The rectum and bladder volumes varied from 34.2 to 267.2 cc and 89.9 to 441.9 cc respectively (mean 89.7, SD 49.2 and mean 228.3, SD 114.7).

All patients received full-course IMRT treatments to a dose of 79.2 Gy to PTV in 44 fractions. For inverse IMRT treatment planning, we used a 6-coplanar non-opposed beam arrangement at 225, 270, 0, 75, 105 and 135 degree angles. Fields were selected so that all entrance and exit beams were spaced about the patient. The plan was generated on a commercial Corvos treatment planning system (Nomos Radiation Oncology, a division of North American Scientific, PA, USA). For all plans we defined dose volume constraints as given in Table 2. Deliveries were modelled using actual beam data for delivery with a Clinac-iX linear accelerator using a millennium 120 multileaf collimator in dynamic mode (Varian Medical Systems, Palo Alto, CA, USA). For all of the cases we developed treatment plans using 6 MV and 10 MV intensity-modulated beams with identical dose volume constraints. The dose volume histograms (DVHs) for the 6-MV and 10-MV plans were compared for PTV and for critical structures such as the rectum, bladder, femoral heads, small intestine and urethra. We also defined the conformal index to compare the treatment plans. The conformal index was defined as the ratio of the 95% isodose volume divided by the PTV volume that is enclosed by the 95% isodose line, since we selected the 95% isodose line as our reference. From this definition the closer the conformal index approaches 1.0, the more conformal is the treatment plan. We also calculated the integral dose surrounding normal tissue by integrating the dose over all voxels within the volume.

RESULTS

The dose distributions for a sample patient along axial, coronal and sagittal planes are shown in Fig. 1 and 2 for 6 MV and 10 MV

Table 1. Patient characteristics for the cohort

Patient number	AP (cm)	Lat (cm)	Prostate Volume (cc)	PTV Volume (cc)	Rectum Volume (cc)	Bladder Volume (cc)
1	25	37	16.8	38.9	34.2	89.9
2	20	34	30.9	70.8	38.1	99.2
3	22	36	33.2	68.6	47.4	99.9
4	25	40	34.8	64.9	61.0	110.4
5	21	38	36.5	79.3	61.3	112.2
6	20	36	40.1	89.7	69.9	119.0
7	23	36	40.5	89.9	70.3	125.1
8	18	34	47.6	88.4	71.1	127.4
9	21	35	48.9	90.6	71.4	161.1
10	23	38	50.9	99.0	71.9	170.6
11	22	39	57.3	104.8	77.7	223.5
12	22	38	62.8	112.9	78.4	241.0
13	28	39	63.6	132.0	79.8	252.6
14	24	40	64.8	113.8	81.0	261.2
15	26	40	68.2	133.0	86.7	323.6
16	21	38	80.7	135.7	95.2	333.6
17	27	38	105.8	178.5	121.3	374.2
18	30	40	121.2	190.9	124.5	380.1
19	27	39	145.3	237.1	129.3	381.9
20	22	39	181.9	270.9	267.2	441.9

Table 2. The optimization constraints used for all IMRT plans

Structure	Goal (Gy)	Volume below goal in %	Minimum (Gy)	Maximum (Gy)
Prostate target	79.2	5	76	83
Seminal vesicles target	65.0	5	62	79
Structure	**Goal (Gy)**	**Volume above limit in %**	**Minimum (Gy)**	**Maximum (Gy)**
Tissue	76	0	0	79
Bladder	50	25	1	65
Femoral heads	40	10	1	50
Rectum	50	20	1	65
Small intestine	30	5	1	35
Urethra	35	5	1	40

photon beams respectively. The dose volume histograms for PTV and various critical normal structures are shown in Fig. 3 for both 6 MV and 10 MV photon beams.

The PTV dosimetry details regarding doses received by 98%, 95% and 92% of PTV are given in Table III. Differences in doses received by 95% of PTV for the 10 MV photon beam

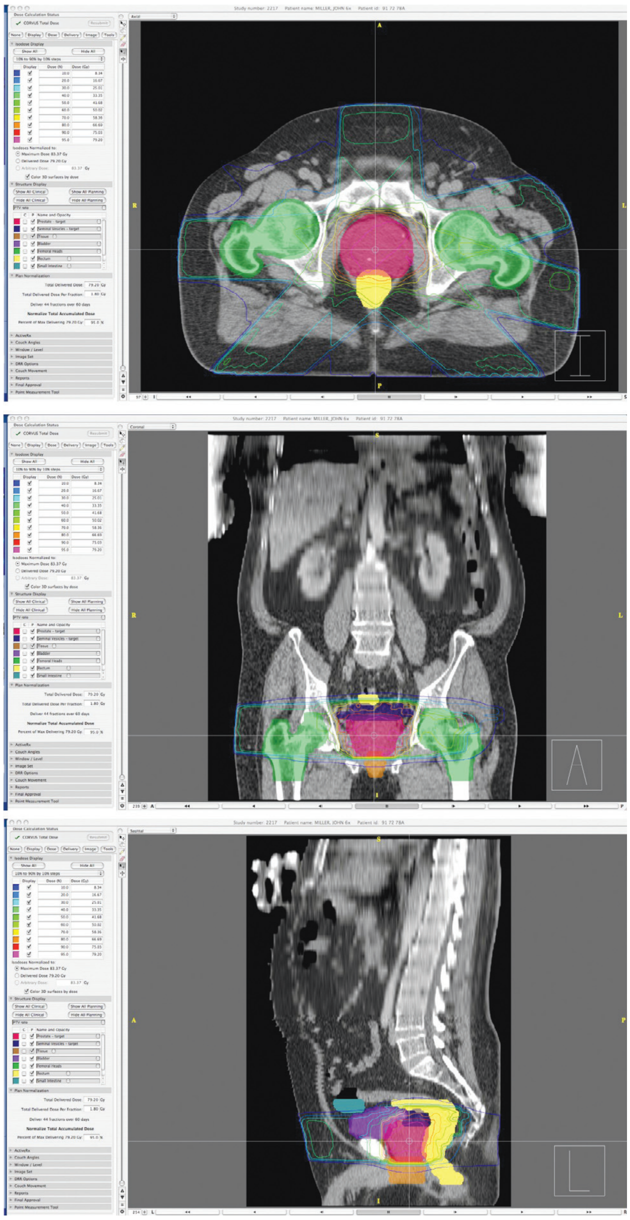

Fig. 1. Dose distribution along axial, coronal and sagittal planes for 6 MV photon beam

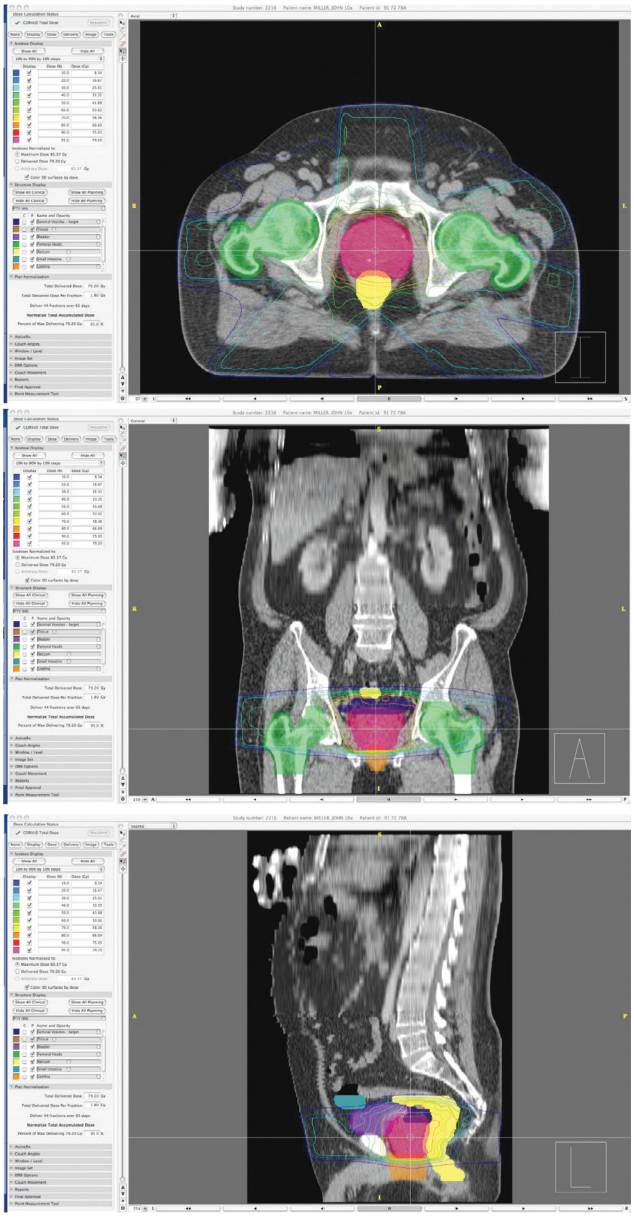

Fig. 2. Dose distribution along axial, coronal and sagittal planes for 10 MV photon beam

versus the 6 MV photon beam are indicated in Table IV. Fig. 4 shows the percentage dose of prescription dose received by each patient for 98%, 95% and 92% of PTV. Bladder dosimetry data regarding mean dose to bladder, volume in cc receiving >65 Gy and volume in percentage receiving >65 Gy are given in Table V. Bladder doses in Gy and percentage for 17% and 15% of volumes are given in Table VI. Fig 5. shows the % volume receiving >65 Gy, and percentage dose received by 15 and 17% volume.

Rectum dosimetry data regarding mean dose to rectum, volume in cc receiving >65 Gy and volume in percentage receiving >65 Gy are given in Table VII. Rectum doses in Gy and percentage for 17% and 15% of volumes are given in Table VIII. Fig 6. shows the % volume receiving >65 Gy, percentage dose received by 17% volume and percentage dose re-

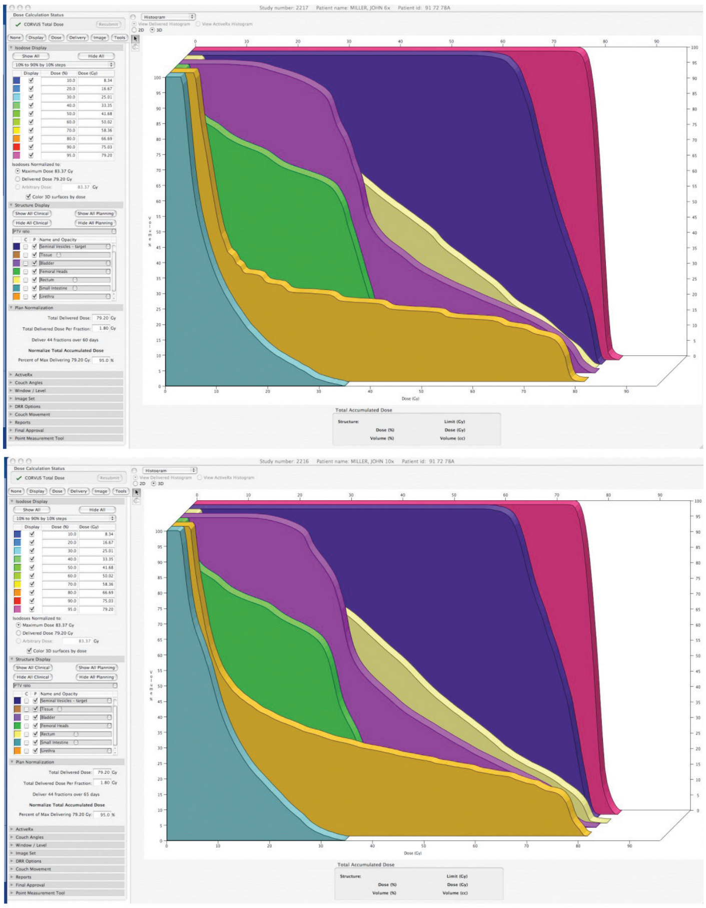

Fig. 3. Dose volume histograms for 6MV and 10 MV photon beams

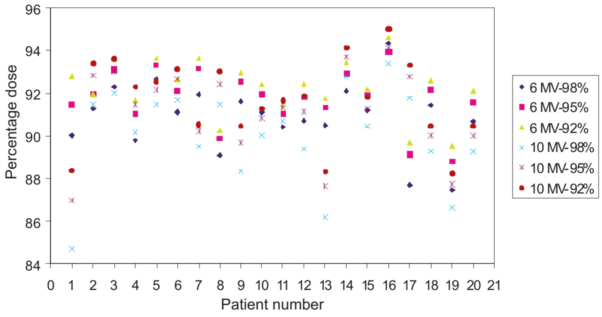

Fig. 4. Precentage dose of prescription dose received by each patient

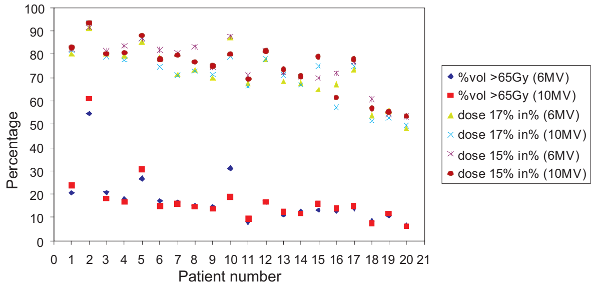

Fig. 5. Bladder dosimetry data

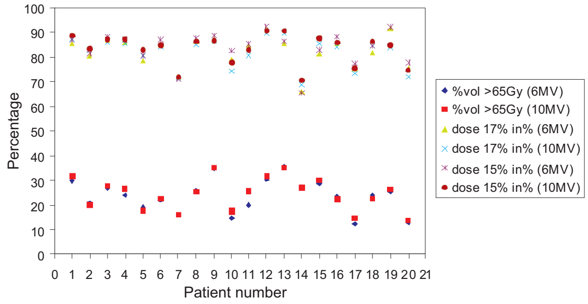

Fig. 6. Rectum dosimetry data

ceived by 15% volume. Normal tissue integral doses for the twenty patients included in this study for 6 MV and 10 MV photon beams are depicted in Table IX. Conformity index values for these patients are given in Table X.

DISCUSSION

Pirzkall et al. [20] examined the influence of energy and number of beams on nontarget dose when using intensity-modulated radiation therapy (IMRT) to treat deep-seated targets. Ten patients with prostate cancer (36–226 cc) treated locally to 75.6 Gy were studied. IMRT plans were created for 6-, 10-, and 18-MV photons using 4, 6, 9, and 11 coplanar nonopposed fields. Plans, normalized to cover 95% of the target volume, were analyzed using: (a) conformity index (CI) at 105%, 100%, 95%, 90%, 80%, 70%, 50% of prescribed dose; (b) prescription isodose line (PI); (c) minimum dose to target (Tarmin); (d) maximum dose to tissue (Tismax); (e) dose to rectum/bladder/penis bulb; (f) integral nontarget dose (ID). Because CI evaluates dose independently of location, tissue was also divided into “near region” (NR: 1-cm thick shell surrounding target) and “far region” (FR: tissue minus NR) volumes that were evaluated at the same levels as CI. Results: The target and sensitive structure met-

Table 3. PTV dosimetry details

Patient Number	PTV Volume (cc)	Dose (Gy) received by % of PTV					
		98% PTV		95% PTV		92% PTV	
		6 MV	10 MV	6 MV	10 MV	6 MV	10 MV
1	38.91	71.32	67.08	72.45	68.90	73.52	70.01
2	70.81	72.31	72.48	72.86	73.55	72.86	74.00
3	68.63	73.10	72.89	73.74	73.67	74.13	74.14
4	64.85	71.11	71.41	72.10	72.48	72.63	73.11
5	79.29	73.38	72.48	73.89	73.00	74.19	73.31
6	89.70	72.17	72.63	72.97	73.41	73.37	73.76
7	89.95	72.82	70.88	73.79	71.45	74.19	71.72
8	88.37	70.58	72.44	71.17	73.22	71.49	73.69
9	90.56	72.56	69.97	73.31	71.03	73.62	71.65
10	99.01	72.16	71.32	72.84	71.94	73.16	72.31
11	104.79	71.60	71.83	72.11	72.32	72.44	72.59
12	112.86	71.83	70.78	72.71	72.19	73.20	72.77
13	132.04	71.66	68.28	72.33	69.40	72.68	69.97
14	113.84	72.95	73.49	73.62	74.22	74.02	74.57
15	132.99	72.23	71.64	72.78	72.30	73.02	72.72
16	135.66	74.71	73.96	74.44	74.54	74.96	75.23
17	178.50	69.44	72.69	70.61	73.49	71.02	73.89
18	190.91	72.44	70.73	73.00	71.32	73.36	71.64
19	237.10	69.25	68.61	70.33	69.47	70.92	69.89
20	270.91	71.82	70.69	72.52	71.29	72.94	71.63

rics were the same for all plans. However, although there was little difference in NR volume exposed to dose, regardless of energy or number of fields, there was a significant increase in FR volume exposed to dose, at all levels, for low energy/few field plans compared to high energy/many fields (e.g., > 50 cc > 65 Gy). This effect disappeared with > 9 fields regardless of energy. With IMRT, the use of 6 MV photons with less than 9 fields may result in an increase in dose in regions distant from the target volume (e.g., near the skin surface), even though the CI and sensitive structure metrics may indicate good conformance of high dose to the target volume itself. The clinical significance of this increased dose distant from the target, in terms of complications, remains to be determined.

An inverse planning technique using 6-MV intensity-modulated photon beams was developed by Sun and Ma [25] for treating large-size patients with prostate cancer. Comparisons of treatment plans using 6-MV and 18-MV intensity-modulated beams were carried out for a cohort of 10 patient cases. For these cases, they analyzed the dependence of plan quality on the beam energies and found that 6-MV beams resulted in plans equivalent to those for 18-MV beams both for targets and for critical structures such as the rectum and bladder. The differences between the plans in the integral dose and the mean dose to the normal tissue surrounding the target were found to be small, in contrast to those for 3D conformal plans. Our findings showed that the low entrance dose of the high-energy photon beams is mostly compensated by the high exit dose for even exceptionally large patients. In conclusion, 6-MV intensity-modulated beams are a feasible choice for treating large-size

Table 4. Difference in percentage of dose received by 95% of PTV

Patient number	PTV Volume (cc)	Difference in percentage of dose received by % of PTV (10 MV vs 6 MV) 95 % PTV
1	38.9	-4.5
2	70.8	0.9
3	68.6	-0.1
4	64.9	0.5
5	79.3	-1.1
6	89.7	0.6
7	90.0	-3.0
8	88.4	2.6
9	90.6	-2.9
10	99.0	-1.1
11	104.8	0.3
12	112.9	-0.7
13	132.0	-3.7
14	113.8	0.8
15	133.0	-0.6
16	135.7	0.1
17	178.5	3.6
18	190.9	-2.1
19	237.1	-1.1
20	270.9	-1.6

patients with prostate cancer, provided that proper inverse planning techniques are adopted.

Three dimensional conformal radiation therapy (3DCRT) for prostate cancer is most commonly delivered with high-energy photons, typically in the range of 10–21 MV. With the advent of intensity-modulated radiation therapy (IMRT), an increase in the number of monitor units (MU) relative to 3DCRT has led to a concern about secondary malignancies. This risk becomes more relevant at higher photon energies where there is a greater neutron contribution. Subsequently, the majority of IMRT prostate treatments being delivered today are with 6–10 MV photons where neutron production is negligible. However, the absolute risk is small [Hall, E. J. Intensity-modulated radiation therapy, protons, and the risk of second cancers. Int J Radiat Oncol Bio Phys 65, 1–7 (2006); Kry, F. S., Salehpour, M., Followill, D. S., Stovall, M., Kuban, D. A., White, R. A., and Rosen, I. I. The calculated risk of fatal secondary malignancies from intensity-modulated radiation therapy. Int J Radiat Oncol Bio Phys 62, 1195–1203 (2005)] and therefore it has been suggested that the use of 18 MV IMRT may achieve better target coverage and normal tissue sparing such that this benefit outweighs the risks. This study investigated whether 18 MV IMRT offers better target coverage and normal tissue sparing. Computed tomography (CT) image sets of ten prostate cancer patients were acquired and two separate IMRT plans were created for each patient. One plan used 6 MV beams, and the other used 18 MV, both in a coplanar, non-opposed beam geometry. Beam arrangements and optimization constraints were the same for all plans. Boer et al. [26] included a comparison and discussion of the total integral dose, neutron dose conformity index, and total number of MU for plans generated with both energies.

Weiss et al. [27] analyzed the supposed benefits of low over high photon energies for the radiotherapy of lung cancer. For 13 patients, 6- and 18-MV IMRT planning was performed using identical planning objectives and dose constraints. Plans were compared according to dose–volume histogram (DVH) analysis including conformity and homogeneity indices (CI and HI) and overall plan quality (composite score CS), considering also magnitude and location of planning target volumes (PTVs). With 6-MV plans, CSs were better in 11/13, HIs in 10/13 and CIs in 6/13 patients compared with 18-MV plans. Six-MV plans resulted in better normal tissue sparing except for specified dose levels to the thorax and spinal cord. On average differences between 6 and 18 MV both for the PTV and normal tissues were not statistically significant ($p > 0.05$). Considering size and location of the PTVs as well as their relative position to normal tissue, overall no significant differences between 6 and 18 MV were observed. Conclusions: On average no clinically or statistically significant differences between 6- and 18-MV plans were observed. High photon energies should therefore not be excluded a priori when a dose-calculation algorithm is utilized that accurately accounts for heterogeneities.

Table 5. Bladder dosimetry data

Patient number	Bladder (cc)	Bladder dosimetry data					
		Mean dose (Gy)		Volume in cc receiving >65Gy		Volume in % receiving >65Gy	
		6 MV	10 MV	6 MV	10 MV	6 MV	10 MV
1	89.86	46.21	47.1	18.30	21.36	20.36	23.77
2	99.18	62.62	64.47	54.18	60.71	54.63	61.21
3	99.92	46.93	44.53	20.76	17.99	20.78	18.00
4	110.39	37.92	40.03	19.53	18.49	17.69	16.75
5	112.16	49.8	49.84	29.68	34.39	26.46	30.66
6	118.99	44.06	42.42	20.47	17.69	17.2	14.87
7	125.11	40.6	39.12	19.57	16.59	16.26	15.77
8	127.35	42.89	40.26	19.20	18.54	15.08	14.56
9	161.10	35.06	28.64	20.90	21.80	14.53	13.53
10	170.63	50.2	43.25	52.84	32.06	30.97	18.79
11	223.49	37.99	38.31	17.92	20.85	8.02	9.33
12	240.99	38.97	39.24	40.53	40.46	16.82	16.79
13	252.56	28.11	28.5	27.60	31.01	10.93	12.28
14	261.16	28.85	28.83	31.86	30.56	12.2	11.70
15	323.58	34.35	24.49	42.13	50.35	13.02	15.56
16	333.61	21.33	32.19	42.60	46.04	12.77	13.8
17	374.22	34.24	35.85	52.35	55.16	13.99	14.74
18	380.07	19.66	19.20	31.81	28.51	8.37	7.50
19	381.94	2.53	2.17	30.12	31.10	10.66	11.52
20	441.92	19.33	19.77	29.52	28.06	6.68	6.35

Madani et al. [28] compared 6 MV and 18 MV photon intensity-modulated radiotherapy (IMRT) for non-small cell lung cancer. Doses for a cohort of 10 patients, typical for our department, were computed with a commercially available convolution/superposition (CS) algorithm. Final dose computation was also performed with a dedicated IMRT Monte Carlo dose engine (MCDE). CS plans showed higher D95% (Gy) for the GTV (68.13 vs 67.36, p = 0.004) and CTV (67.23 vs 66.87, p = 0.028) with 18 than with 6 MV photons. MCDE computations demonstrated higher doses with 6 MV than 18 MV in D95% for the PTV (64.62 vs 63.64, p = 0.009), PTVoptim (65.48 vs 64.83, p = 0.014) and CTV (66.22 vs 65.64, p = 0.027). Dose inhomogeneity was lower with 18 than with 6 MV photons for GTV (0.08 vs 0.09, p = 0.007) and CTV (0.10 vs 0.11, p = 0.045) in CS but not MCDE plans. 6 MV photons significantly (D33%; p = 0.045) spared the oesophagus in MCDE plans. Observed dose differences between lower and higher energy IMRT plans were dependent on the individual patient. Selection of photon energy depends on priority ranking of endpoints and individual patients. In the absence of highly accurate dose computation algorithms such as CS and MCDE, 6 MV photons may be the prudent choice.

Many lung cancer patients who undergo radiation therapy are treated with higher energy photons (15–18 MV) to obtain deeper penetration and better dose uniformity. However, the longer range of the higher energy recoil electrons in the low density medium may cause lateral electronic disequilibrium and degrade the target coverage. To compare the dose homogeneity achieved with lower versus higher en-

Table 6. Bladder doses in Gy and percentage for 17% and 15% of volumes

Patient number	Bladder (cc)	Bladder dosimetry data							
		17% of bladder receiving dose				15% of bladder receiving dose			
		6 MV		10 MV		6 MV		10 MV	
		Gy	%	Gy	%	Gy	%	Gy	%
1	89.86	67.02	80.39	68.13	81.72	68.54	82.2	69.24	83.05
2	99.18	76.22	91.42	77.82	93.34	76.44	91.69	78.05	93.62
3	99.92	66.72	80.03	65.71	78.8	67.84	81.37	67.03	80.4
4	110.39	66.18	79.38	64.69	77.6	69.94	83.53	67.34	80.78
5	112.16	71.15	85.34	72.36	86.79	72.54	87.01	73.37	88.01
6	118.99	65.4	78.46	62.01	74.38	68.07	81.65	64.85	77.78
7	125.11	62.09	71.26	63.1	70.96	65.66	80.65	64.98	79.78
8	127.35	61.08	73.26	60.68	72.78	69.56	83.44	64.06	76.84
9	161.1	37.46	69.66	38.49	71.36	37.64	74.62	38.54	75.02
10	170.63	72.62	87.11	65.76	78.88	73.12	87.71	66.56	79.89
11	223.49	56.31	67.54	55.07	66.06	59.06	70.85	57.9	69.46
12	240.99	64.49	77.35	64.51	78.15	67.88	81.42	67.19	81.4
13	252.56	56.9	68.3	59.16	70.96	60.37	72.41	61.36	73.61
14	261.16	58.61	67.76	55.17	66.77	58.61	70.3	58.95	70.72
15	323.58	55.93	64.93	62.51	74.99	60.11	69.79	65.81	78.94
16	333.61	56.2	67.42	62.5	57.1	59.9	71.86	64.2	61.36
17	374.22	61.3	73.52	62.52	74.99	63.84	76.57	64.74	77.66
18	380.07	44.81	53.75	42.71	51.23	50.2	60.6	47.43	56.8
19	381.94	46.65	55.75	47.12	52.73	49.63	54.25	48.69	55.23
20	441.92	39.94	47.91	41.31	49.55	44.4	53.23	44.51	53.39

ergy photon beams, Wang et al. [29] performed a dosimetric study of 6 and 15 MV three dimensional (3D) conformal treatment plans for lung cancer using an accurate, patient-specific dose-calculation method based on a Monte Carlo technique. A 6 and 15 MV 3D conformal treatment plan was generated for each of two patients with target volumes exceeding 200 cm3 in an in-house treatment planning system in routine clinical use. Each plan employed four conformally shaped photon beams. Each dose distribution was recalculated with the Monte Carlo method, utilizing the same beam geometry and patient-specific computed tomography (CT) images. Treatment plans using the two energies were compared in terms of their isodose distributions and dose-volume histograms (DVHs). The 15 MV dose distributions and DVHs generated by the clinical treatment planning calculations were as good as, or slightly better than, those generated for 6 MV beams. However, the Monte Carlo dose calculation predicted increased penumbra width with increased photon energy resulting in decreased lateral dose homogeneity for the 15 MV plans. Monte Carlo calculations showed that all target coverage indicators were significantly worse for 15 MV than for 6 MV; in particular, the portion of the planning target volume (PTV) receiving at least 95% of the prescription dose (= V95) dropped dramatically for the 15 MV plan in comparison to the 6 MV. Spinal cord and lung doses were clinically equivalent for the two energies. In treatment planning of tumours that abut lung tissue, lower energy (6 MV) photon beams should be preferred over higher energies (15–18 MV) because of the significant loss of lateral dose equilibrium for high-energy

Table 7. Rectum dosimetry data

Patient number	Rectum (cc)	Rectum dosimetry data					
		Mean dose (Gy)		Volume in cc receiving >65Gy		Volume in % receiving >65Gy	
		6 MV	10 MV	6 MV	10 MV	6 MV	10 MV
1	34.17	52.84	52.84	10.19	10.86	29.81	31.78
2	38.09	8.87	10.33	7.93	7.62	20.82	20.00
3	47.43	46.94	43.69	12.64	13.08	26.64	27.58
4	60.97	48.28	43.78	14.63	16.30	24.00	26.74
5	61.32	35.61	36.61	11.76	10.85	19.18	17.69
6	69.85	55.88	54.04	15.24	15.82	21.82	22.65
7	70.26	12.57	12.26	11.33	11.40	16.12	16.22
8	71.13	46.63	44.86	18.33	18.15	25.77	25.51
9	71.35	54.04	55.07	24.83	25.14	34.80	35.23
10	71.89	35.8	33.1	10.68	12.59	14.85	17.51
11	77.65	43.56	43.88	15.45	19.85	19.90	25.56
12	78.37	46.08	44.41	23.93	25.08	30.54	32.00
13	79.83	52.94	54.31	28.50	28.28	35.70	35.43
14	80.99	47.31	49.08	21.89	21.87	27.03	27.00
15	86.72	51.44	53.4	24.97	26.02	28.79	30.00
16	95.24	42.37	43.11	22.67	21.11	23.80	22.17
17	121.32	32.87	35.34	15.14	17.74	12.48	14.62
18	124.53	37.79	38.04	29.89	27.99	24.00	22.48
19	129.3	36.06	33.48	32.69	33.88	25.28	26.20
20	267.18	27.56	26.35	33.66	36.42	12.60	13.63

beams in the low-density medium. Any gains in radial dose uniformity across steep density gradients for higher energy beams must be weighed carefully against the lateral beam degradation due to penumbra widening.

Aoyama et al. [30] designed a study to evaluate the integral dose (ID) received by normal tissue from intensity-modulated radiotherapy (IMRT) for prostate cancer. Twenty-five radiation treatment plans including IMRT using a conventional linac with both 6 MV (6MV-IMRT) and 20 MV (20MV-IMRT), as well as three-dimensional conformal radiotherapy (3DCRT) using 6 MV (6MV-3DCRT) and 20 MV (20MV-3DCRT) and IMRT using TomoTherapy (6MV) (Tomo-IMRT), were created for 5 patients with localized prostate cancer. The ID (mean dose _ tissue volume) received by normal tissue (NTID) was calculated from dose–volume histograms. The 6MV-IMRT resulted in 5.0% lower NTID than 6MV-3DCRT; 20 MV beam plans resulted in 7.7%–11.2% lower NTID than 6MV-3DCRT. Tomo-IMRT NTID was comparable to 6MV-IMRT. Compared with 6MV-3DCRT, 6MV-IMRT reduced IDs to the rectal wall and penile bulb by 6.1% and 2.7%, respectively. Tomo-IMRT further reduced these IDs by 11.9% and 16.5%, respectively. The 20 MV plan did not reduce IDs to those structures. The difference in NTID between 3DCRT and IMRT is small. The 20 MV plans somewhat reduced NTID compared with 6 MV plans. The advantage of TomoTherapy over conventional IMRT and 3DCRT for localized prostate cancer was demonstrated in regard to dose sparing of rectal wall and penile bulb while slightly decreasing NTID as compared with 6MV-3DCRT.

Table 8. Rectum doses in Gy and percentage for 17% and 15% of volumes

Patient number	Rectum (cc)	Rectum dosimetry data							
		17% of rectum receiving dose				15% of rectum receiving dose			
		6 MV		10 MV		6 MV		10 MV	
		Gy	%	Gy	%	Gy	%	Gy	%
1	34.17	71.3	85.53	72.15	87.41	72.46	86.92	73.23	88.72
2	38.09	67.04	80.9	69.03	82.8	68.97	81.4	70.66	83.6
3	47.43	72.49	86.95	71.79	86.12	73.54	88.21	72.38	87.3
4	60.97	71.64	85.93	71.26	85.47	72.63	87.12	72.73	87.24
5	61.32	65.58	78.66	63.23	80.64	67.43	80.89	69.1	82.89
6	69.85	70.58	85.06	70.85	84.2	72.06	86.83	71.34	84.87
7	70.26	69.2	71.88	69.9	71.51	69.8	70.99	69.99	72.02
8	71.13	71.9	86.3	70.95	85.1	73.11	87.7	71.93	86.28
9	71.35	72.58	87.06	71.85	86.19	74.06	88.83	72.34	86.77
10	71.89	65.88	79.02	61.96	74.32	68.73	82.44	64.82	77.75
11	77.65	70.48	84.54	67.34	80.77	70.97	85.13	69.11	82.89
12	78.37	76.28	91.5	74.91	89.85	77.11	92.5	75.77	90.89
13	79.83	73.8	85.64	74.89	89.84	74.42	86.41	75.69	90.79
14	80.99	70.12	65.66	70.99	68.67	70.22	65.39	70.89	70.63
15	86.72	67.06	81.46	71.48	85.74	69.02	82.79	73.08	87.66
16	95.24	71.37	85.6	70.3	84.32	73.6	88.29	71.78	86.1
17	121.32	62.71	75.22	61.2	73.4	64.66	77.56	62.74	75.26
18	124.53	68.27	81.89	70.4	84.45	70.64	84.73	72.06	86.43
19	129.3	76.1	91.28	69.82	83.74	76.8	92.12	70.68	84.78
20	267.18	62.75	75.27	60.05	72.04	64.67	77.6	62.26	74.68

The dose delivered to patients by photons and neutrons outside the radiation fields when beam intensity modulation conformal radiotherapy is given is estimated. These estimates are then used to compute the risk of secondary cancers as a sequela of the radiation therapy. The x-ray and neutron leakage accompanying two beam intensity modulation techniques delivered by currently available linear accelerators was estimated by Followill et al. [31] for 6 MV, 18 MV and 25 MV x-ray energies. Estimates of whole body dose equivalents were determined using leakage measurements reported in the literature and treatment parameters derived for two modulated beam intensity conformal therapy techniques. Risk values recommended by the National Council on Radiation Protection and Measurements (NCRP) were used to estimate the resulting risk of fatal radiation induced cancer for 70.00 Gy prescribed tumour dose. The computed worst case risks of secondary cancers increased in the range from 1.00% for 6 MV x-rays to 24.4% for 25 MV x-rays. Careful consideration should be made of the risks associated with secondary whole body radiation before implementation of beam intensity-modulated conformal therapy at x-ray energies greater than 10 MV.

Howell et al. [32] calculated effective doses from the delivery of 6 MV, 15 MV, and 18 MV conventional and intensity-modulated radiation therapy (IMRT) prostate treatment plans. ICRP-60 tissue weighting factors were used for the calculations. Photon doses were measured in a phantom for all beam energies. Neutron spectra were measured for 15 MV and 18 MV and ICRP-74 quality conversion factors used to calculate ambient dose equivalents.

Table 9. Normal tissue integral doses

Patient number	6 MV photons cc-Gy	10 MV photons cc-Gy	% Difference
1	159989.48	151341.40	-5.4
2	138753.20	135832.08	-2.1
3	133354.80	117883.90	-11.6
4	198935.02	194702.36	-2.1
5	241913.70	228639.60	-5.5
6	108752.73	108473.16	-0.3
7	124763.16	120816.88	-3.2
8	134033.285	129453.56	-3.4
9	142978.22	136364.69	-4.6
10	135379.29	135708.68	0.2
11	125606.28	124896.64	-0.6
12	173798.72	164494.72	-5.4
13	159454.72	159855.36	0.3
14	122377.1	123221.08	0.7
15	62439.96	58182.69	-6.8
16	192734.75	174083.00	-9.7
17	205308.35	194100.45	-5.5
18	167917.7	162501.00	-3.2
19	174800.87	165255.43	-5.5
20	253894.93	235271.83	-7.3

Table 10. Conformity indices for 6 MV and 10 MV photon beams

Patient number	6 MV photons	10 MV photons
1	0.885	0.955
2	0.687	0.804
3	0.863	0.826
4	0.953	0.853
5	0.847	0.764
6	0.745	0.922
7	0.781	0.814
8	0.774	0.856
9	0.887	0.796
10	0.815	0.854
11	0.811	0.886
12	0.853	0.939
13	0.867	0.832
14	0.844	0.885
15	0.812	0.855
16	0.937	0.917
17	0.887	0.872
18	0.844	0.745
19	0.884	0.814
20	0.965	0.955

The ambient dose equivalents were corrected for each tissue using neutron depth dose data from the literature. The depth-corrected neutron doses were then used as a measure of the neutron component of the ICRP protection quantity, organ equivalent dose. IMRT resulted in an increased photon dose to many organs. However, the IMRT treatments resulted in an overall decrease in effective dose compared to conventional radiotherapy. This decrease correlates with the ability of an intensity-modulated field to minimize the dose to critical normal structures in close proximity to the treatment volume. In a comparison of the three beam energies used for the IMRT treatments, 6 MV resulted in the lowest effective dose, while 18 MV resulted in the highest effective dose. This is attributed to the large neutron contribution for 18 MV compared to no neutron contribution for 6 MV.

We evaluated a cohort of 20 prostate cancer patients wherein the PTV ranged from 38.91 cc to 270.91 cc (roughly a ratio of 7.0). Except for energy all the treatment planning parameters were the same for these patients. Percentage of doses received by % of PTV was higher for 6 MV photons compared to 10 MV photons for 12 patients. Percentage doses received by 15% of bladder volume were higher for 10 MV photons. Percentage doses received by 15% of rectum volume were also higher for 10 MV photons.

Normal tissue integral doses for the twenty patients were higher for 6 MV photons compared to 10 MV photons, though by a small percentage. There was no particular advantage seen for 10 MV photons in terms of conformity index values. Since 10 MV photons lie on the threshold energy border for the induction of photoneutrons from the accelerator components, we recommend the use of 6 MV photons for IMRT of prostate cancer to achieve higher tumour control and acceptable complication rate.

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