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Original article

Optimal planning parameters for simultaneous boost IMRT treatment of prostate cancer using a Beam Modulator™

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ABSTRACT

Objective: To determine the optimum energy and beam arrangement for prostate intensity-modulated radiation therapy (IMRT) delivery using an Elekta Beam Modulator™ linear accelerator, in order to inform decisions when commissioning IMRT for prostate cancer.

Methods: CMS XiO was used to create IMRT plans for a prostate patient. Arrangements with 3, 5, 7, 9 and 11 equally spaced fields, containing both a direct anterior and a direct posterior beam were used, with both 6 MV and 10 MV photons. The effects of varying the maximum number of iterations, leaf increment, number of intensity levels and minimum segment size were investigated. Treatment plans were compared using isodose distributions, conformity indices for targets and critical structures, target dose homogeneity, body dose and plan complexity.

Results: Target dose conformity and homogeneity and sparing of critical structures improved with an increasing number of beams, although any improvements were small for plans containing more than five fields. Set-ups containing a direct posterior field provided superior conformality around the rectum to anterior beam arrangements. Mean non-target dose and total number of monitor units were higher with 6 MV for all beam arrangements. The dose distribution resulting from seven 6 MV beams was considered clinically equivalent to that with five 10 MV beams.

Conclusion: Methods have been developed to plan IMRT treatments using XiO for delivery with a Beam Modulator™ that fulfil demanding dose criteria, using many different set-ups. This study suggests that 6 MV photons can produce prostate IMRT plans that are comparable to those using 10 MV. Work is ongoing to develop a complete class solution.

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1. Introduction

With intensity-modulated radiation therapy (IMRT), the radiation intensity within each field is varied according to a fluence map calculated by a treatment planning system (TPS) to provide the desired dose distribution, which is specified in terms of dose and dose-volume constraints for targets and organs at risk (OAR).[1] The increased control over dose distributions achieved with optimised intensity-modulated beams can provide a significant advantage when treating complex geometries, for example where a target has a concave shape around a critical organ such as the prostate around the rectum. Studies show improved outcomes for localised prostate cancer following IMRT compared to three-dimensional conformal radiation therapy (3DCRT).[2–4] Dose escalation can significantly improve prostate-specific antigen (PSA) relapse-free survival due to improved local tumour control.[5] Radiation-induced damage to surrounding critical structures becomes a limiting factor in 3DCRT techniques, with the rectum being the principal OAR. Intensity-modulation can improve dose conformality, confining irradiation more closely to target volumes to allow further increases in tumour dose while reducing the normal tissue volumes irradiated.

IMRT is being commissioned in Leeds for the treatment of prostate patients entered into the Conventional or Hypofractionated High Dose Intensity Modulated Radiotherapy for Prostate Cancer (CHHIP) trial,[6] a study investigating the hypothesis that shorter radiotherapy courses delivering a higher dose per fraction may improve tumour control in localised prostate cancer for a given level of radiation related side effects. Prostate radiotherapy is currently delivered in Leeds using 10 MV photons from Beam Modulator™ (BM) linear accelerators, and plans are generated using the XiO TPS (Computerised Medical Systems Inc., St. Louis, USA). The BM is an innovative type of treatment head from Elekta Oncology Systems Ltd.,[7] the physical and dosimetric characteristics of which have been described previously.[8] Fig. 1 shows the head design. The multileaf collimator (MLC) consists of 40 leaf pairs. Each leaf projects a width of 4 mm at the isocentre rather than the conventional 1 cm. The maximum beam size at the isocentre is 16 cm × 21 cm. The leaves are capable of interdigitation, which is not possible in the standard Elekta MLC head.[9] There is no other movable collimation, e.g. backup diaphragms, in the MLC head of a BM.

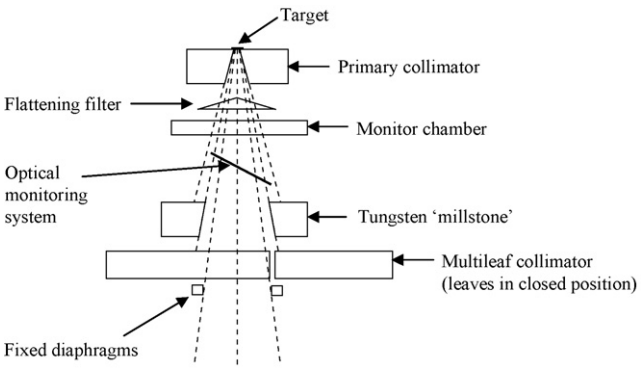

Fig. 1 – Schematic diagram of the Elekta Beam Modulator™ treatment head.

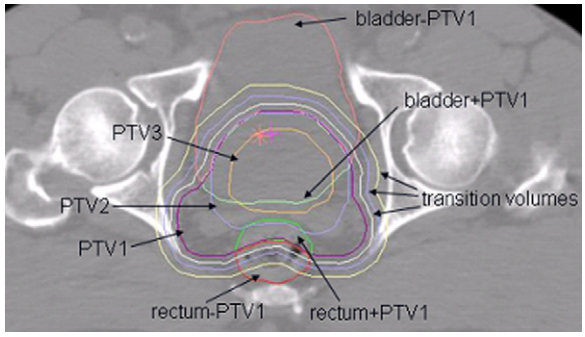

Fig. 2 – Planning structures contoured in XiO. PTV, planning target volume.

A 'class solution' is required for a new type of treatment, to provide a starting point from which the majority of plans can be created, making it possible to plan large numbers of treatments with the minimum appropriate adjustments for individual patients. This should specify a set of planning parameters including photon energy, number and arrangement of beams, and dose limits and penalties to be used by the optimisation algorithm.

There is a range of literature on energy selection, and selection of other IMRT parameters such as number of beams and beam orientations for prostate treatment,[10–21] some with conflicting conclusions or recommendations. However, there is currently no published literature regarding IMRT planning using XiO for delivery with a BM, and a class solution must be determined for this specific set-up. It is possible that previous observations may be specific to particular TPSs and linear accelerator designs. The aim of this study is to determine the optimum energy and beam configuration for prostate IMRT delivery using an Elekta BM by comparing achievable treatment plans, in order to inform decisions when commissioning IMRT for prostate cancer. The CHHIP protocol[6] requires a simultaneous boost technique delivering different doses to three nested planning target volumes (PTV), while plans in the reviewed literature involve at most two targets. In addition, results concerning the effects on dose distributions of varying the number of fields and photon energy will add to the knowledge base for this application.

2. Methods

2.1. *Generation of treatment plans*

Plans were created with XiO v4.33.02 for a prostate patient with moderate risk of seminal vesicle involvement, using test patient data from the CHHIP trial QA information.[6] For this patient group PTV1 is the prostate and seminal vesicles with a 10 mm isotropic margin (see Fig. 2). PTV2 and PTV3 are defined as prostate only plus a margin of 10 mm and 5 mm respectively, with 5 mm and 0 mm towards the rectum. Minimum and maximum doses to a structure are defined as those received by 99% and 1% of the volume respectively. The CHHIP conventional 2 Gy fractionation schedule was used, in which the core high-dose region is prescribed 74 Gy. The protocol

Table 1 – Normal tissue dose-volume constraints for the CHHIP trial.[6] Values in brackets are for guidance only.

	Dose (Gy) for 2 Gy/# schedule	Dose (%)	Maximum volume
Rectum	30	41	[80%]
	40	54	[70%]
	50	68	60%
	60	81	50%
	65	88	30%
	70	95	15%
	74	100	3%
Bladder	50	68	50%
	60	81	25%
	74	100	5%
Femoral heads	50	68	50%
Bowel	50	68	17 cm^3
Urethral bulb	50	68	[50%]
	60	81	[10%]

requires minimum coverage of PTV3 with the 95% (70.3 Gy) isodose, with median dose in the range 99–101%. PTV2 requires minimum coverage with 91% of 74 Gy (67.3 Gy), and PTV1 with 76% (56.2 Gy). Dose-volume constraints are specified for the rectum, bladder, femoral heads and bowel, with additional guidance levels for the urethral bulb (Table 1).

The optimiser in XiO acts to minimise an overall cost function, which is the sum of individual objective functions specified for each target and OAR to establish suitable dose or dose-volume goals. Two parameters associated with these objectives can be varied in order to achieve a combination of different goals. Increasing the *weight* of a particular dose or dose-volume objective increases its relative importance with respect to other objectives. *Power* is used to increase the magnitude of the penalty applied to voxels with doses that violate a structure's objectives. Overlap priority is determined in XiO by the *rank* assigned to each structure, with voxels lying inside more than one being governed by objectives specified for the organ with the lowest number. PTV3 was therefore given the lowest rank, with increasing values for PTV2 and PTV1. A suitable minimum dose limit was assigned to each target to achieve the required coverage, and a maximum limit to constrain high dose. As found by others,[10,11] it was necessary to prescribe more stringent dose limits than those required, since the optimisation algorithm cannot satisfy all the demands placed on it, and segmentation degrades plans.

In regions of high dose gradient, it can be useful to create *transition volumes* to help transition the dose between two areas with different prescriptions.[22] Additional structures were contoured around PTV1 as shown in Fig. 2, to aid the transition from high dose within the targets to low dose in surrounding tissue, to make dose fall off more rapidly outside the prostate. After investigating various combinations of margins, PTV1 was grown in three dimensions by 0.3 cm, 0.6 cm and 1.0 cm. By requiring the optimisation algorithm to treat these as OARs, each with a maximum dose limit equal to the minimum dose of the structure immediately inside, conformity of the 76% isodose to PTV1 was considerably improved.

Others who have developed class solutions for prostate IMRT have found it necessary to define artificial structures in order to achieve a conformal dose distribution.[5,10] Fig. 2 illustrates all the structures that were used for planning in this study. The rectum was divided into two separate structures to provide greater control over isodose shaping around PTVs in the region of overlap. A maximum dose limit of 70 Gy for the part overlapping the targets (rectum + PTV1) pushes areas of high dose within the targets away from the rectum. A more stringent maximum dose (corresponding to the minimum PTV1 dose) was applied to the part of the rectum outside PTV1 (rectum – PTV1), together with a dose-volume constraint to control the rectum dose-volume histogram (DVH). Similarly, a maximum dose limit was applied to the part of the bladder inside the targets (bladder + PTV1), to reduce the bladder volume receiving high dose. It was not necessary to specify

Structure	Type	Rank	Objective	Dose(Gy)	Volume(%)	Weight	Power	Status
PTV3	Target	1	Maximum	75.00	0	600	2.0	On
			Minimum	74.00	100	500	2.2	On
bladder+PTV1	OAR	2	Maximum	69.00	0	400	2.0	On
PTV2	Target	2	Maximum	72.00	0	200	2.3	On
			Minimum	72.00	100	600	2.6	On
rectum+PTV1	OAR	2	Maximum	70.00	0	100	2.5	On
PTV1	Target	5	Maximum	65.00	0	100	2.0	On
			Minimum	59.00	100	600	2.3	On
rectum-PTV1	OAR	6	Maximum	56.00	0	1000	2.0	On
			Dose Volume	40.00	50	100	2.0	On
PTV1+0.3	OAR	7	Maximum	67.00	0	300	2.0	On
PTV1+0.6	OAR	8	Maximum	45.00	0	300	2.0	On
PTV1+1.0	OAR	9	Maximum	30.00	0	300	2.0	On

Fig. 3 – Example IMRT prescription, for posterior five-field arrangement at 10 MV. PTV1 + 0.3, PTV1 + 0.6 and PTV1 + 1.0 denote the three transition volumes surrounding planning target volume 1, formed by adding margins of 0.3 cm, 0.6 cm and 1.0 cm respectively. Weights range from 1 to 1000 and powers from 2.0 to 5.0. OAR, organ at risk.

constraints for the femoral heads or bowel in the prescription, as doses were well within CHHIP limits for all plans.

An initial treatment plan was generated using five equally spaced fields including a direct posterior beam, since several centres use arrangements very similar to this,[5,10,11] with 10 MV photons. The rank and dose and/or dose-volume objectives for each target and OAR were varied, together with weights and powers, to determine a combination that satisfied all the CHHIP requirements. Fig. 3 shows the resulting prescription. The beam arrangement and energy were then varied to generate a series of plans with 3, 5, 7, 9 and 11 equally spaced fields, containing both a direct anterior and a direct posterior beam, using both 6 MV and 10 MV photons. DVHs were used to compare doses to targets and OARs with the criteria laid out in the CHHIP protocol, to determine whether dose distributions were acceptable. In most cases some constraints were no longer met, and slight modifications to one or more dose limits and/or penalties in the original prescription were usually necessary (optional CHHIP constraints were not always met). Forward planning was also performed for comparison, using a conventional 10 MV four-beam box (FBB) technique with an additional coned-down boost field entering from each direction.

The impact of a number of IMRT planning parameters on dose distributions was investigated for a 10 MV plan with a five-beam posterior arrangement, to decide on suitable values to be used in all the plans for this study. A conformity index was calculated for each PTV in order to compare plans (defined as the ratio of the total volume covered by 95% of the prescribed dose to the target volume enclosed by that isodose). *Step increments* (beamlet size in the direction of leaf travel at the isocentre) in the allowed range of 0.3–2.0 cm were investigated. To produce a deliverable plan, each beam is divided into a number of smaller segments. The ideal intensity maps are quantised into a user-defined number of *discrete intensity levels*. A *minimum segment size* is also specified; any segments with an equivalent field size below this value are deleted. Plans resulting from segmentation with minimum square segments across the allowed range of 0.0–3.0 cm, and 4–10 discrete intensity levels were compared. A maximum of 60 iterations in the optimisation was found to achieve the objectives for all structures. Final dose calculations were performed on a 0.2 cm × 0.2 cm × 0.2 cm grid.

2.2. *Comparison of treatment plans*

A number of figures of merit were used to quantitatively evaluate treatment plans using values measured from DVHs, in addition to a visual assessment of isodose distributions. A clinical oncologist who specialises in radiotherapy of urological cancers viewed the dose distributions, to see whether the ranking of plans using objective measures supported clinical opinion.

Dose conformality to each PTV was assessed using a conformity index (CI), defined for a reference isodose (RI), taken to be the minimum dose covering the target, as:

$$\mathrm{CI} = \frac{\mathrm{PTV_{RI}}}{V_{\mathrm{RI}}} \tag{1}$$

where $\mathrm{PTV_{RI}}$ and V_{RI} denote the target volume and total tissue volume receiving at least the reference dose. The conformal index (COIN) defined by Baltas et al.[23] was used to incorporate a measure of normal tissue avoidance. COIN values were calculated for the minimum isodose covering each PTV using Eq. (2):

$$\mathrm{COIN} = \frac{\mathrm{PTV_{RI}}}{\mathrm{PTV}} \times \frac{\mathrm{PTV_{RI}}}{V_{\mathrm{RI}}} \times \prod_{i=1}^{N_{\mathrm{CO}}} \left(1 - \frac{V_{\mathrm{CO,RI},i}}{V_{\mathrm{CO},i}}\right) \tag{2}$$

where N_{CO} is the number of critical organs and V_{CO} is critical organ volume. COIN combines the quality of target coverage with irradiation of both non-critical healthy tissues and critical organs in a single parameter, each component of which tends towards 1 in the ideal case. Although this index was originally proposed for brachytherapy, Feuvret et al.[24] discuss its application to external beam radiotherapy, where it can be useful in high-precision techniques associated with a very high dose gradient.

Another avoidance measure, a comprehensive quality index (CQI) made up of individual quality indices (QI) for surrounding critical structures based on their maximum dose D_{max}, used by Sheng et al.[25] to compare techniques for treating sinus tumours, was applied to this comparison of 6 MV and 10 MV plans for N OARs:

$$\mathrm{CQI} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{QI_i} = \frac{1}{N}\sum_{i=1}^{N} \frac{D^{6}_{\mathrm{max}\,i}}{D^{10}_{\mathrm{max}\,i}} \tag{3}$$

An inhomogeneity index[26] was used to compare dose uniformity within the targets:

$$\prod = \frac{D_{\mathrm{max}} - D_{\mathrm{min}}}{D_{\mathrm{mean}}} \tag{4}$$

where D_{max}, D_{min} and D_{mean} are the maximum, minimum and mean PTV dose.

Mean and maximum doses received by the whole body, non-target tissue, and tissue more than 1 cm away from the boundary of PTV1 were assessed for all plans. The total numbers of segments and monitor units (MU) were also compared, as measures of plan complexity.

3. Results

3.1. *IMRT planning parameters*

Fig. 4 shows the variation of PTV conformity indices with IMRT planning parameters. PTV1 dose conformity improved with decreasing step size (Fig. 4a), with a smaller improvement observed for PTV2. Step increments above 0.8 cm led to significant degradation of dose distributions. An increment of 0.3 cm provided only a very small improvement compared to 0.6 cm, while calculation time approximately doubled. For segmented plans (with 5–10 intensity levels, minimum segment size 1.6 cm), the total number of segments increased by 10–14 per centimetre decrease in leaf increment.

Dose conformity improved for all three PTVs with a smaller minimum segment size, as shown in Fig. 4b. Conformity

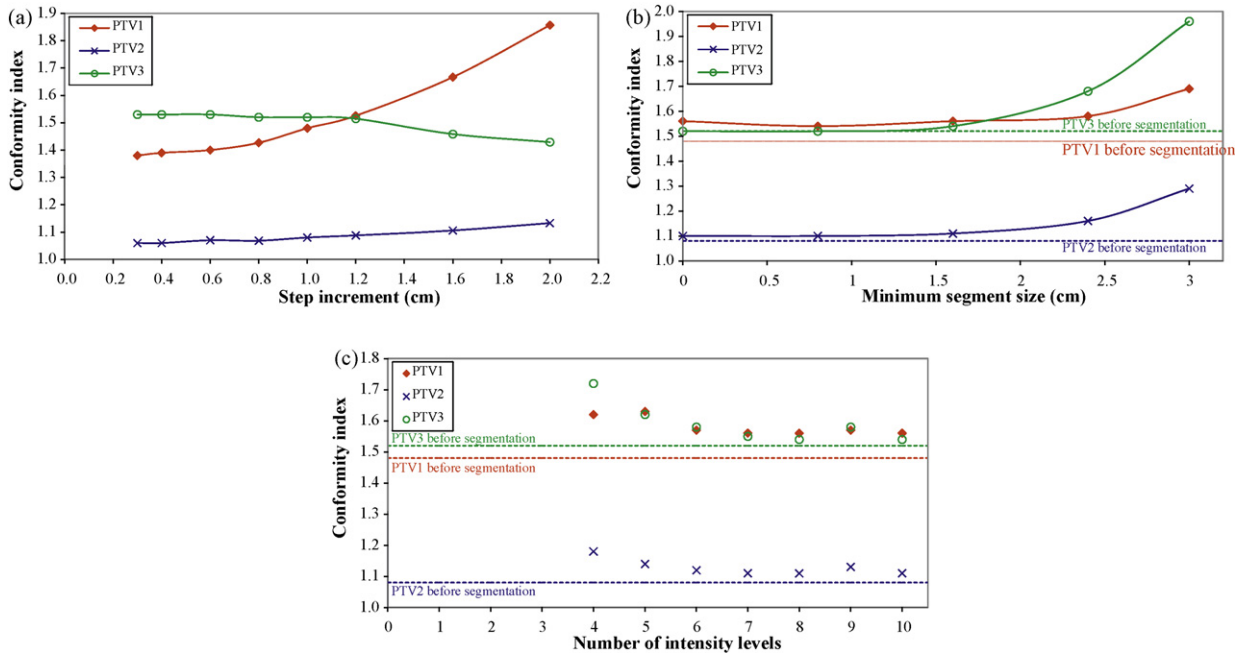

Fig. 4 – Effect of varying IMRT planning parameters on planning target volume (PTV) conformity indices (defined for each PTV as the ratio of the total volume covered by 95% of the prescribed dose to the volume of the target enclosed by that isodose). (a) Step increment (no segmentation). (b) Minimum segment size (step increment 1.0 cm, 10 discrete intensity levels). (c) Number of discrete intensity levels (step increment 1.0 cm, minimum segment size 1.6 cm). Dashed lines indicate values before segmentation.

indices for PTV2 and PTV3 began to diverge significantly from values before segmentation for a minimum segment size above 1.6 cm. Target doses increased when this parameter was increased above 1.6 cm. Although increasing the number of discrete intensity levels does not necessarily improve a dose distribution, conformity generally improved with an increasing number of levels (Fig. 4c), as did target dose homogeneity. Dose conformity was considered inferior with fewer than six or seven intensity levels. On average, the total number of segments increased by eight per centimetre decrease in minimum

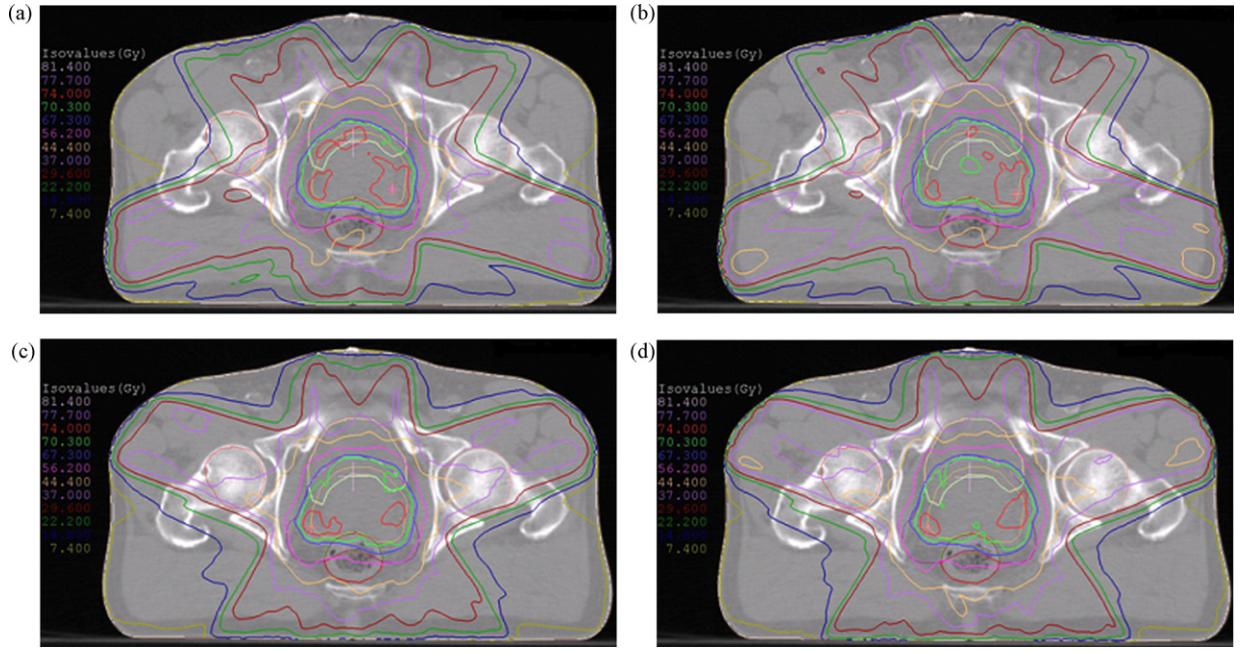

Fig. 5 – Transverse dose distribution through the isocentre for five-field IMRT plans. (a) Posterior beam arrangement at 10 MV. (b) Posterior beam arrangement at 6 MV. (c) Anterior beam arrangement at 10 MV. (d) Anterior beam arrangement at 6 MV.

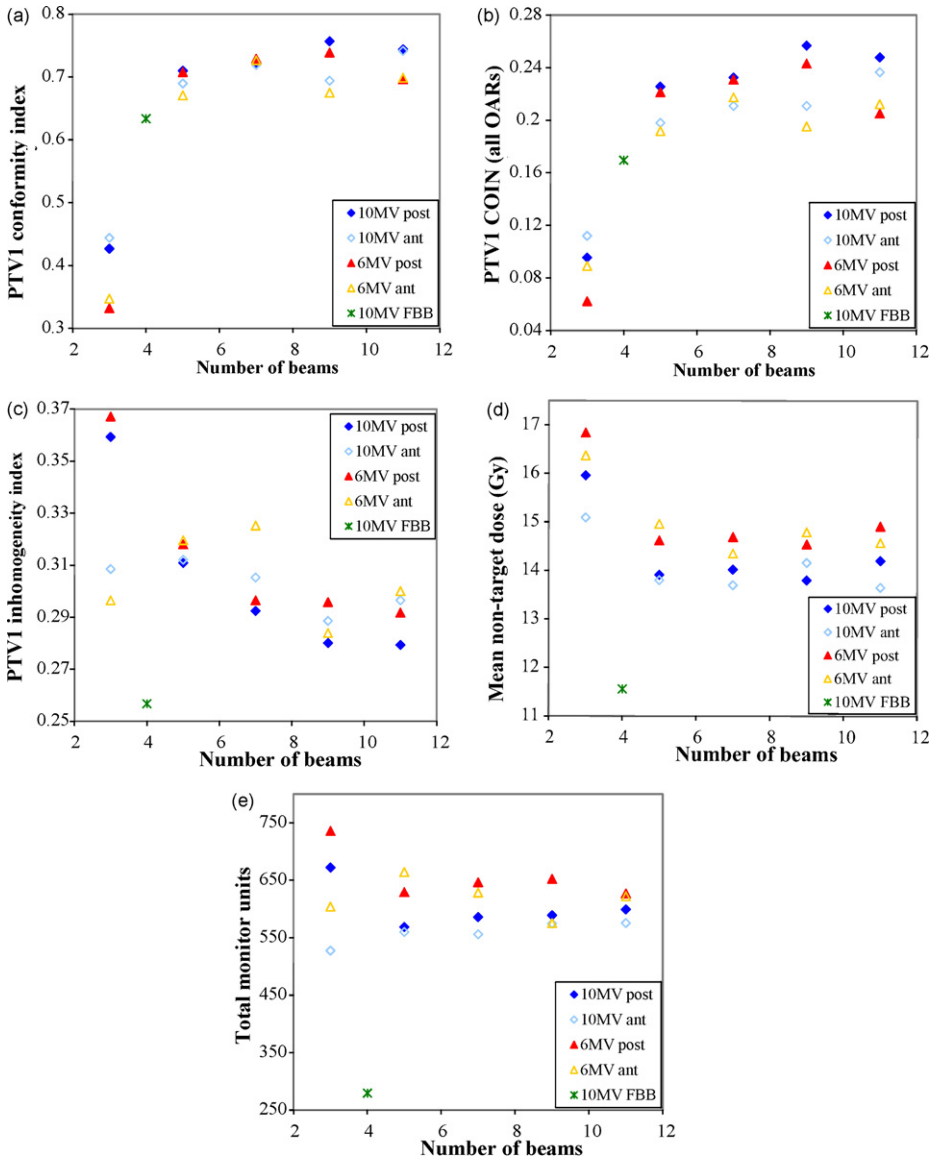

Fig. 6 – Examples of graphs comparing quantitative figures of merit between treatment plans. (a) Planning target volume (PTV) 1 conformity index (CI). (b) Conformal index (COIN) including all organs at risk (OAR) at dose level of PTV1. (c) PTV1 inhomogeneity index. (d) Mean dose outside PTV1. (e) Total number of monitor units. FBB, four-beam box.

segment size, and by six or seven with each additional intensity level.

3.2. *Comparison of treatment plans*

3.2.1. *Visual inspection of isodose distributions*

Fig. 5 shows dose distributions in a typical slice for the five-field plans. In general as the number of beams increased, isodoses conformed slightly more tightly to PTVs and high dose was constrained in a smaller region around the prostate, with improvements in target dose homogeneity. More accurate shaping of the 56.2 Gy (76%) isodose around PTV1 where it overlaps the rectum, in terms of both target coverage and rectum sparing, was achieved with a posterior beam arrangement. For a given beam set-up, 10 MV photons gave comparable or better target dose homogeneity and conformity than 6 MV, with lower doses outside the prostate. High-dose regions arose near the patient surface in plans using three or five 6 MV beams; Fig. 5b and d shows tissue in posterior/anterior oblique beams receiving 44 Gy.

3.2.2. *Conformity*

A clear advantage in both target volume CIs and COIN values was demonstrated from using more than three beams, with only small improvements observed as the number of fields was increased above five. Fig. 6a and b illustrates this for the minimum dose covering PTV1. For a given beam arrangement there appears to be some advantage in the use of 10 MV photons. At the dose level of PTV3, CI improved by an average of 7% compared to 6 MV plans, and COIN values were higher, on average by 10% when all OARs were considered. The FBB provided better dose conformity than three-field plans, but IMRT

with five or more beams was superior in terms of CI and COIN values. QIs for the rectum and bladder lay within 1.5% of 1.0 in all cases. Considering maximum rectal doses, 10 MV plans were slightly superior for five beam arrangements and 6 MV for four. For the bladder, eight beam arrangements were better for 10 MV and only one for 6 MV, although the bladder will be full during treatment so most of this dose will actually be delivered to urine. Combined CQIs for both OARs lay in the range 0.991–1.012; eight beam arrangements were better with 10 MV and two with 6 MV.

3.2.3. *Homogeneity*

Dose uniformity within the targets generally improved with an increasing number of beams, as shown in Fig. 6c for PTV1. For a posterior beam arrangement, homogeneity was found to improve with up to seven or nine beams. In many cases 10 MV plans showed better homogeneity than 6 MV; within PTV3 10 MV was superior in all cases except the three-beam anterior arrangement. The FBB provided superior target dose uniformity compared to IMRT with even the highest numbers of beams.

3.2.4. *Body dose*

The mean dose to non-target tissues decreased substantially when five or more fields were used (Fig. 6d). It was consistently higher in 6 MV plans, by an average of 6% across the different beam arrangements. The maximum dose in tissue more than 1 cm away from PTV1 showed a similar drop between three and five beams, with much smaller changes with additional fields. This was higher at 6 MV for all but one beam arrangement, with the difference between the two energies decreasing as the number of fields increased.

3.2.5. *Plan complexity*

Each intensity-modulated beam used approximately the same number of segments. Therefore the total number of segments required to deliver a treatment increased in proportion with the number of fields (on average by 11 or 12 with each additional beam). The total number of MU was higher for 6 MV photons by up to 19% (Fig. 6e). A posterior beam arrangement required more MU in all but one case. The range of total MU between plans decreased with an increasing number of beams, converging to approximately 600. The forward plan used only eight segments and required less than half the average number of MU for IMRT plans.

4. Discussion

4.1. *IMRT planning parameters*

The increase in number of segments (and therefore treatment delivery time) with decreasing leaf increment or minimum segment size, and increasing number of intensity levels, must be weighed against the improvements in dose distributions. A step increment of 0.6 cm was chosen as a compromise between achieving desired dose distributions and limiting the calculation time. This is in line with the recommendation of Wu.[27] A smaller leaf movement between segments increases flexibility in controlling individual beamlet intensities. A minimum segment size of 1.6 cm was chosen, since no significant improvement was observed when smaller segments were permitted, and dosimetry becomes less reliable for very small fields. Eight intensity levels were used for this study, as this was found to provide acceptable dose distributions in all cases.

4.2. *Comparison of treatment plans*

Both photon energies were able to provide adequate target coverage and OAR sparing to satisfy the requirements of the CHHIP protocol with all the beam arrangements investigated. It was more difficult to meet all the criteria when using fewer fields, and this took many attempts with only three beams. It was possible to achieve an acceptable dose distribution using forward planning, although this irradiated more healthy tissue than IMRT with five or more beams (shown by lower CI and COIN values). The greater dose heterogeneity within targets observed in IMRT plans compared to a FBB is generally recognised as a trade-off for the increased OAR sparing achieved with IMRT.[10]

Energy selection is critical for conventional external beam radiotherapy. Lower photon energies have traditionally been used to treat superficial tumours, while higher energies provide greater penetration, enabling delivery of maximum dose at depth without injuring shallow tissues when irradiating deep-seated tumours. However, high energies introduce problems including increasingly diffuse beam boundaries due to the greater lateral range of secondary electrons. Laughlin et al.[12] showed that the narrower penumbra of lower-energy megavoltage X-ray beams results in a tighter dose distribution around a target, minimising irradiation of nearby OARs, although regions near beam entry ports receive higher dose.

Observations that IMRT treatment planning depends much less on energy optimisation, such as a study by Söderström et al.[13] suggesting that 6 MV photons can provide effective treatments in most cases, have led to the manufacture of IMRT-dedicated single intermediate energy linear accelerators, the advantages and disadvantages of which have been discussed by Subramanian and Gibbons.[14] Subramanian argues that IMRT should be performed using 6–8 MV photons, for which dosimetry characteristics are better understood in heterogeneous media and shielding is less expensive. Benefits of low energies include minimising total body dose from head leakage, internal scatter and secondary neutrons. Advocating the use of 10 MV or above, Gibbons points out that low-energy treatments deposit high dose in regions peripheral to the target, and generally require a more complex plan containing a greater number of fields, beam segments and MU. This increases treatment delivery times, integral dose and irradiation of surrounding organs.

Prostate cancer has conventionally been treated using X-rays at 10 MV or above, but a lower energy may be sufficient with IMRT. A number of studies have compared 6 MV prostate IMRT with higher energies. Lu et al.[15] found that 6 MV beams can achieve comparable dose distributions and DVHs to those resulting from 15 MV. De Boer et al.[16] demonstrated no clinical benefit from the use of 18 MV compared to 6 MV, and Sun and Ma[17] showed that 6 MV photons can produce equivalent plans to 18 MV even for exceptionally large patients.

The clinical oncologist consulted in the present study would be equally satisfied using either photon energy. High entrance dose at 6 MV gave rise to superficial high-dose regions in anterior/posterior oblique beams. This effect decreased with an increasing number of beams, since fewer MU entered through each. Although five beams provided an acceptable dose distribution at 10 MV, additional fields are likely to be necessary if 6 MV is to be used; with seven beams the high-dose regions disappeared. This supports the observations of Pirzkall et al.[18], who argue that IMRT does depend on energy for deep-seated targets. While plans at 6 MV, 10 MV and 18 MV had comparable dose distributions surrounding the prostate, a significant increase was observed in the volume of tissue further than 1 cm from the target boundary receiving dose when using either low energy or few fields. However, that study indicated that a minimum of nine fields is likely to be necessary for 6 MV prostate plans, while at 10 MV six fields should be acceptable.

Adverse skin reactions are therefore a concern for low-energy treatment of deep-seated targets, particularly in large patients. Thermoluminescence dosimetry measurements performed on the surface of a phantom[19] have shown that although skin doses during prostate IMRT treatments are higher with 6 MV than 18 MV, they are significantly reduced for both energies compared with 3DCRT, and doses from 6 MV IMRT are substantially lower than 18 MV 3DCRT. Chow et al.[20] performed phantom measurements using metal oxide semiconductor field effect transistor (MOSFET) detectors, which showed that for a given number of fields surface doses are higher at 6 MV than 15 MV, but the difference decreased from approximately 30% to 5% as the number of IMRT beams was increased from five to nine.

More MU are needed to deliver the required target dose with 6 MV photons due to their lower penetrability, resulting in higher whole body doses. The FBB gave a significantly lower mean non-target dose than all the IMRT plans as it delivered fewer MU, although the maximum dose was higher than IMRT plans using five or more fields due to large regions in the lateral beams receiving up to 48 Gy.

Differences in conformity and inhomogeneity indices between 6 MV and 10 MV plans were not considered clinically significant. This supports previous studies that have demonstrated no significant variation in conformity or critical structure doses between prostate IMRT plans using photon energies between 6 MV and 18 MV.[16,18] In these IMRT studies, lower energies do not provide the improvement in dose conformity observed with non-modulated beams.[12] The modulation of beam intensities to achieve desired target and OAR doses works independently of beam energy. The small improvements in CI and COIN values seen with 10 MV photons compared to 6 MV for a given beam arrangement do appear to contradict a study in which conformal index values were the same or slightly better for 6 MV prostate IMRT plans compared to 18 MV.[17] However, results will depend on the particular definitions adopted for indices, and none of the previous studies used a BM where the different leaf size may affect conformity.

To minimise the time required to plan and deliver treatments and perform dosimetric verification, it is desirable to use the minimum number of beams that can achieve a satisfactory treatment plan. Stein et al.[21] found that the optimum number of equispaced coplanar intensity-modulated 15 MV photon beams to treat a typical prostate tumour increases with prescription dose, ranging from 3–5 for 70 Gy to 7–9 for 81 Gy. Optimisation of beam orientations was found to significantly improve dose distributions compared to equiangular arrangements only with five or fewer fields.

Increasing the number of beams provides greater control, and others have reported similar improvements in conformality[20] and target dose homogeneity.[21] No significant advantage was perceived from the use of more than five beams for 10 MV or seven beams for 6 MV, while three-field plans were inferior, in agreement with Mott et al.[10] An arrangement containing a direct posterior field was preferred due to the increased rectum sparing achieved through improved conformity around the concave posterior PTV boundaries. This supports the prediction of Stein et al.[21], that intensity-modulated beams entering from the direction of an OAR partially enclosed by a target allow greater control over dose distributions in this region. The variations in MU and body dose support observations that energy becomes less important as the number of IMRT beams increases, suggesting that the value of using high energy to treat deep-seated targets decreases with an increasing number of beams.[18,20]

4.3. *Future work*

The development of a class solution requires further investigation to determine an optimal set of inverse planning parameters and prescription for the chosen beam arrangement and photon energy. In order to perform a meaningful comparison between treatment plans, the values used in this study were not optimised for any particular set-up, so that differences between prescriptions were minimised and all other parameters could remain constant. This will need to be tested on a number of additional patient datasets, in order to establish a robust class solution that provides a good starting point in most cases. Dosimetric verification measurements have been performed using a Semiflex 0.125 cm^3 ionisation chamber and films. These gave good agreement with XiO following remodelling of the BM data specifically for the small fields associated with IMRT.

5. Conclusion

IMRT treatments with a Beam Modulator^{TM} linear accelerator have been successfully planned, and delivered to a phantom. Planning methods have been developed with the XiO TPS to generate acceptable plans fulfilling the demanding dose criteria of the CHHIP trial, using many different set-ups. This involved varying planning parameters in a systematic way to determine appropriate values. A number of plan evaluation parameters have been explored for comparing treatment plans, and these have been related to clinical decisions.

6 MV photons can achieve an equivalent dose distribution to 10 MV for prostate IMRT, provided a sufficient number of treatment fields is used to avoid high-dose regions near beam entry points. This study suggests that seven beams are necessary with 6 MV while only five are required with 10 MV. The clinical oncologist who reviewed the plans considered that the

dosimetric differences observed between a seven-field 6 MV plan and a five-field 10 MV plan for this patient would be unlikely to be clinically significant. A beam arrangement containing a direct posterior field provided superior conformality around the rectum compared to an anterior arrangement. Although using 6 MV slightly increases treatment calculation and delivery times and the number of QA measurements required, it will avoid the need to commission a second energy for IMRT, and is therefore preferred. Work is ongoing to develop a complete class solution and carry out all necessary dosimetric verification.

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