A quantitative study of IMRT delivery effects in commercial planning systems for the case of oesophagus and prostate tumours

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Abstract

This study focuses on understanding the impact of IMRT delivery effects on commercial treatment-planning systems such as Pinnacle (ADAC Laboratories Inc.) and CadPlan/Helios, (Varian Medical Systems) planning systems. The study was performed for tumours of the oesophagus and prostate and pelvic nodes. The oesophagus was planned with the ADAC planning system assuming IMRT delivery, via multiple static fields (MSF) or compensators, using the Elekta SL25 with a MLC component. While, for the prostate and pelvic nodes IMRT planning was performed with Cadplan/Helios assuming a dynamic delivery (DMLC) using the Varian 120-leaf Millennium multileaf collimator (MLC).

In a commercial planning system, since IMRT delivery effects are not included into the optimisation process, fluence renormalisation is required such that the mean delivered PTV dose equals the initial prescribed PTV dose. The study was divided into two main parts: (a) analysing the dose distribution within the PTV, produced by each of the delivery techniques, after the delivered fluence has been renormalised such that all IMRT techniques have their mean PTV dose equal to the initially prescribed PTV dose; and (b) studying the impact of the IMRT delivery technique on the surrounding critical organs such as the spinal cord, lungs, rectum, bladder etc.

In preparing the optimum fluence profile for delivery, the PTV dose has been “smeared” by the IMRT delivery techniques. In the case of the oesophagus, the critical organ spinal cord received a significantly greater dose than initially planned, due to the delivery effects. The increase in the spinal cord dose is of the order of 2-3 Gy. In the case of the prostate and pelvic nodes, the IMRT delivery effects led to an increase in approximately 2 Gy in the dose delivered to the secondary PTV, the pelvic nodes. In addition to this, the small bowel, rectum and bladder have received an increased dose of the order of 2-3 Gy to 50% of their total volume.

IMRT delivery techniques strongly influence the delivered dose distributions for the oesophagus and prostate/pelvic nodes tumour sites and these effects are not accounted for in the Pinnacle (ADAC Laboratories Inc.) and the CadPlan/Helios, (Varian Medical Systems) planning systems.

1. Introduction

The treatment planning of carcinoma of the oesophagus is particularly difficult, due to the location of the tumour and surrounding critical organs. The planning target volume (PTV) is situated in close proximity to the spinal cord and is, usually, completely surrounded by the lungs, a radiosensitive organ.

Surgery remains the main treatment for carcinoma of the oesophagus, despite the long-term survival rates following oesophagectomy being poor. Radiotherapy is commonly used for primary tumours of the oesophagus that are deemed unsuitable for surgery. In particular, in the upper third of the oesophagus, radiotherapy may be considered as the treatment of choice. The 3 and 5 year survival figures following radiotherapy obtained at Christie Hospital by Sykes *et al* (1998) were 27 % and 21 %, respectively. In addition to radiotherapy alone, the combination of high-dose radiation therapy with chemotherapy may improve the survival rate and local tumour control (Al-Sarraf *et al* 1994 and Smith *et al* 1998). As shown in these reports, the addition of chemotherapy has been shown to improve survival significantly, with corresponding improvements in loco-regional control and reduction in incidence of distant metastases.

Bedford *et al* (2000), applied three-dimensional conformal radiotherapy techniques with chemotherapy to allow a better conformation of the treated volume. The potential benefit of conformal therapy is the possible dose escalation of the tumour site while avoiding adjacent radiosensitive structures, i.e. lung and spinal cord. Three different treatment plans were created and compared for a cohort of 10 patients. A two-phase treatment plan with conventional fields and blocks (designated by CV2), a two phase conformal plan (CF2) and a three-phase conformal plan (CF3), where the third phase was delivered to the GTV (gross tumour volume) only, were considered for each patient. It was observed that the CF2 technique reduced the volume of lung irradiated to 18 Gy from 19.7 ± 11.8 (1 SD) to $17.1 \pm 12.3\%$, consequently permitting an increase in target dose to 59.1 ± 3.2 Gy without

increasing the mean lung dose. It was observed that the technique CF3 facilitated a prescribed dose 60.7 ± 4.3 Gy to the target, for a spinal cord tolerance of 45 Gy.

The patients with prostate cancer, considered within this study, have a high risk of pelvic nodal involvement or have radiological or pathological evidence of nodal metastases. IMRT has been shown to reduce normal tissue irradiation without sacrificing target coverage compared to conventional techniques (Nutting *et al* 2000 and Zelefsky *et al* 2000). Attempting to treat large volumes within the pelvis benefits from the sparing capabilities of IMRT (Nutting *et al* 2000). The small bowel is in close proximity to the pelvic nodes and the horse-shoe shape of the nodes, makes it a particularly difficult region to treat using conventional methods.

Intensity modulated radiation therapy (IMRT) may provide an improvement over conformal/conventional radiotherapy. IMRT treatment planning is usually performed independently of the delivery method, where the optimisation is performed based on a set of physical or/and biological constraints. When converting the plan, calculated by the planning system, into a deliverable sequence of leaf positions (MSF or DMLC) or compensator thicknesses, the dose delivered to the planning target volume and the organs at risk (OAR) may change depending on the leaf characteristics taken into account during the leaf sequencing. In the present study, a quantitative analysis of the impact of IMRT delivery effects for 3 or 5 fields, uniformly distributed around the patient, for multiple-static fields (MSF), dynamic MLC or compensator delivery techniques has been investigated.

2. Method

2.1 Overview of IMRT delivery techniques: MSF, DMLC or Compensator

In converting the calculated fluence plan from the planning system into a deliverable sequence of leaf position (MSF or DMLC) or compensator thickness, different sequencing algorithms are used. In the case of the MSF technique, the Pinnacle planning system has a step-and-shoot K-means clustering algorithm (Hartigan 1975) that breaks the ideal fluence into smaller groups or clusters of equal value, in the case of the Elekta linac.

In the case of the compensator, the density of the compensation material, width, height, resolution for the compensator and depth of the plane for the compensator shape optimisation are defined. The energy fluence is then iteratively attenuated by the corresponding thickness of the modifier at each optimisation fluence point. A “granular compensator” was selected with spatial resolution of 0.05 cm and material density of 4.9 g/cm³ (approximate density of standard compensator material). The source to compensator distance was 56.6 cm and the compensator was allowed a maximum thickness of 10 cm.

In the case of the DMLC technique, the ‘optimal’ fluences are converted to the ‘actual’ fluences (Varian terms) using the leaf motion calculator (LMC) which designs the leaf motion patterns. The LMC takes into account the various MLC parameters such as maximum leaf span, leaf speed, transmission, rounded end effects and minimum leaf gaps. Since the X and Y jaws do not move during beam on, the maximum leaf span will determine how many carriage positions will be required to deliver the fluence for a given field width (X jaws). The field is split into multiple overlapping fields of the appropriate number of carriage or jaw positions. Although the leaf motions are not fully synchronised, the time of travel across the field is the same for all leaf pairs which helps to reduce the tongue-and-groove effect (Essers *et al* 2001).

2.2. Patient setup and treatment objectives

2.2.1 Oesophagus Tumour Site and ADAC planning system

A patient with oesophageal carcinoma was planned with 3 or 5 field IMRT plans (gantry angles: 0°, 120°, 240° and 0°, 72°, 144°, 216° and 288°) using P³IMRT (Pinnacle, ADAC version 6.0g). The clinical target volumes (CTV), spinal cord and lung parenchyma, were outlined on each image. The CTV region included both the oesophagus tumour and adjacent lymph nodes. The PTV region was generated by adding a three-dimensional margin of 15 mm to the CTV to account for movement and target definition uncertainties.

The goal of the plan was to deliver 55 Gy to the PTV, while maintaining the spinal dose less than or equal to 45 Gy and minimising the dose to the lungs. The spinal cord dose constraint of 45 Gy is conservative. Martel *et al* (1997) and Emami *et al* (1991) have shown that in head and neck cancers, the tolerance dose for the spinal cord is around 50 Gy, with a 5% chance of a complication occurring in 5 years. None of the patients treated by Martel *et al* (1997) developed radiation myelitis, with the spinal cord receiving doses up to 50 Gy.

In addition to the spinal cord dose constraint, the volume of lung irradiated to 18 Gy has been used at the Royal Marsden NHS Trust. In the present study, no more than 20% of the lung could receive more than 18 Gy. The prediction of lung complications at the treatment planning stage is not straightforward. There is no consensus on which dosimetric parameter should be used to reflect the clinical incidence of pneumonitis, however the volume of lung receiving 18 Gy was chosen since it is appropriately conservative (Martel *et al* 1994) to the present study. Cardiac radiation toxicity for carcinoma of the oesophagus is not a major clinical concern because of the small number of long-term survivors. Therefore, the heart was not included as one of the OAR.

2.2.2 Prostate and Pelvic Nodes Tumour Site and Helios/CadPlan planning system

Gantry angles of 180° (posterior), 270° (right lateral), 325° (right anterior oblique), 35° (left anterior oblique), 100° (left posterior oblique) were chosen such that the 5 beams were spread out around the patient, provided good bowel sparing and were not opposing. The treatment was designed to deliver a dose of 70 Gy to the prostate and 50 Gy to the seminal vesicles and pelvic nodes. The prostate CTV was considered to be the entire visible prostate and was grown to a PTV with a 1cm margin. However if the overlap between the PTV and rectum was large then the posterior margin was reduced to 8mm. The nodal CTV was expanded to a PTV with a uniform 5mm margin. The goal dose constraints we have used for the prostate and pelvic node treatment are given in Clark *et al* (2002).

For prostate and pelvic node treatment with five gantry angles, typical beam lengths were 16-18cm and beam widths were 10-18cm. Typical monitor units (MUs) were 95 (for a section of a split field) and 135 (for a maximum width single field). The prescribed dose was 2Gy per fraction to the median of the prostate PTV (Clark *et al* 2002).

2.3 Clinical impact of IMRT delivery effects

An “optimum” IMRT plan was obtained with the planning system. The optimum fluence profiles were then leaf-sequenced in order to generate the leaf positions or compensator thicknesses, to allow the delivery of the planned profile. Each delivered IMRT plan would deliver a slightly different dose to the PTV, from that planned. The delivered IMRT fluence maps are then renormalised such as to attain the prescribed dose to the median of the principal PTV, i.e. 55 Gy for the oesophagus tumour and 70 Gy for the prostate tumour. In the case of the oesophagus tumour site, the impact of clustering the IMRT fluence profiles was studied, where each fluence map was divided into equal fluence levels,

using a tolerance error method equivalent to that described in Bär *et al* (2001). The tolerance errors used for fluence clustering were 2%, 5% and 10%.

In the case of the Helios/CadPlan planning system, several dose/volume values were compared before and after sequencing for the secondary PTV and critical organs (rectum, bladder, etc), for the case of 3 patients with prostate cancer and nodal involvement. These dose/volume values correspond to the dose delivered to 90%, 75%, 50%, 25% and 10% of the volume of the bladder, rectum and small bowel and 95%, 75%, 50%, 25% and 5% of the volume of the PTV (prostate), right and left nodes.

3. Results and discussion

3.1. Oesophagus tumour site and ADAC planning system

3.1.1 Clinical impact of IMRT delivery effects

An “optimum” IMRT plan was obtained with the ADAC planning system with a prescribed dose to the PTV region of 55 Gy. The optimum profiles were then leaf-sequenced in order to generate the leaf positions or compensator thicknesses. These were then calculated to allow the delivery of the planned profile. Each delivered IMRT plan would deliver a different dose to the PTV, from that planned. These differences were in the order of 2-4% and were mainly due to head-scatter and transmission effects associated with the delivery technique, not accounted for during the planning stage. In order to compare the various delivery methods, the plans were all re-normalised such as to deliver a mean dose 55 Gy to the PTV.

The IMRT profiles were delivered using either the MSF or the compensator delivery techniques. In the case of the MSF technique, the fluence profiles were clustered into equal fluence levels, using a tolerance error method equivalent to that described in Bär *et al* (2001). The tolerance errors used were 2%, 5% and 10%.

In figure 1, the DVH obtained for the delivered plans in case of 3 and 5 beams are compared to that planned for the PTV. In delivering the optimum fluence profile, the PTV dose has been “smeared” by both the MSF and the compensator techniques. In the case of the 3 beam delivery, the tolerance error of 2 % has produced the dose distribution that better approximates the planned optimum (OPT_PTV). This is a consequence of the greater number of fluence levels allowed by the 2% than by the 5% and 10% cases.

In the case of the 5 beam plan, the delivered plans for the MSF for 5% and 10% and the compensator are shown to “smear” the dose distribution planned for the PTV. The 2% is not shown due to hardware limitations not allowing the completion of the leaf-sequencing calculation. The compensator has produced the best delivered plan, of all the delivery methods represented for the 5 beam.

In figure 2, the dose distribution obtained on a CT slice of the patient for the 3 beam case, obtained for the (a) optimum plan, and MSF delivery with (a) 2% and (c) 5% tolerance error is shown. In figure 2a, the 98% isodose curve conforms closely to the PTV region represented by the dark red circle. After delivery with the MSF technique, the high

98% isodose covers part of the adjacent lungs. In addition to this, the 80% isodose has significantly changed from the planned distribution (green curve in figure 2a) to the delivered (green curve in figure 2b/c). Therefore, the lungs have received increased dose due to an increased head-scatter and transmission from the delivery technique. The spinal cord is also receiving an increased dose as may be observed comparing the 50% isodose (blue) publishing colours ? curves in figure 2.

3.1.2 Impact of IMRT delivery effects on organs at risk

The DVH for the spinal cord is presented in figure 3 for both the 3 and 5 beam cases. In the case of the 3 beam, the spinal cord has received significantly more dose than initially planned, due to delivery effects. The increase in the maximum dose delivered to the spinal cord is of the order of 2-3 Gy, in addition to an overall increase of 5-10 Gy in the dose delivered to 50% of the total volume of the spinal cord. In the case of the 5 beams, a similar increase in the spinal cord dose is observed, although, the DVH is different between the various delivery methods compared.

In figure 4, the DVH obtained for the left and right lungs are presented. The maximum dose delivered to the lungs increases respectively by 1 and 3 Gy for the 3 and 5 applied beams. For the case of 5 applied beams, the dose delivered to 50% of the lung volume varies dramatic with the tolerance errors used to segment modulated beam profiles. There is no significant difference between the delivered dose to the lungs by the MSF technique for the 2%, 5% and 10% tolerance errors, in the case of the 3 beams. However, in the case of the 5 beams the delivered doses to the lungs by the MSF (5% and 10%) or the compensator are distinctly different. As shown in these results, the IMRT delivery techniques influence strongly the delivered dose distributions for the oesophagus tumour site, with the spinal cord and the lungs as organs at risk.

3.2 Prostate and pelvic nodes and Helios planning system

An “optimum” IMRT plan was obtained with the Helios planning system with a prescribed dose to the PTV region of 70 Gy to the primary prostate tumour and 48 Gy to the nodes. The optimum profiles were then leaf-sequenced in order to generate the leaf positions for the DMLC delivery. These were then calculated to allow the evaluation of the delivered profile and dose distribution. Each delivered IMRT plan would deliver a different dose distribution to the primary PTV, with subsequent increase in dose delivered to the secondary PTV (nodes) and organs at risk (bladder, small bowel and rectum).

The mean dose (over the group of 3 prostate patients) delivered to the volumes of interest in “before” and “after” leaf-sequencing are presented in table 1, for the various dose/volume points studied. In the case of the organs at risk there is an increase of up to 3.3 Gy in the delivered dose to 50% of the total volume of the small bowel. While, the bladder and rectum are respectively subject to 2.15 Gy and 3.03 Gy more dose, delivered to 50% of their total volume. In the case of the small bowel and the rectum the increase in 3 Gy of delivered dose to 50% of the volume, may lead an increase in late radiation complication effects, rectal bleeding, etc. On the overall, the majority of the volumes of the organs at risk (bladder, small bowel and rectum) have received significantly more dose delivered to 90% of their volume. In the case of the rectum, this increase was the largest being of the order of 5 Gy to 90% of its total volume. In the case of the bladder and small bowel the increase was, respectively, 3.79 Gy and 3.14 Gy in the dose delivered to 90% of the total volume.

For the secondary PTV (right and left nodes), the leaf-sequencing of an IMRT “optimum” fluence profile (to be delivered by an MLC) leads to an average increase of, approximately, 2 Gy to 50% of the volume of the nodes, where the dose to the prostate tumour is not significantly altered. This increase in nodal dose may lead to late toxicity or complication effects. In addition to this, both nodes are also receiving more than 3 Gy dose delivered to the majority (90%) of their volume. The increase is due mainly to head scatter and transmission radiation associated with the MLC delivery equipment and that is not accounted for by the Helios planning and optimisation planning system. This overall increase in the delivered dose is only observed for the volumes of interest: bladder, small bowel, rectum and nodes but not the primary PTV/prostate, to which everything is renormalised “after” leaf-sequencing.

4. Conclusions

The impact of IMRT delivery effects on commercial treatment-planning systems such as the Pinnacle planning system (ADAC Laboratories Inc.) and CadPlan/Helios, (Varian Medical Systems) planning systems was evaluated. The study was performed for the oesophagus and prostate (with nodal involvement) tumours irradiated with multiple static fields, DMLC and the compensator delivery technique, after renormalising the delivered fluence such that all IMRT plans have the same mean PTV dose.

In the case of the oesophagus tumour site and using the Pinnacle planning system (ADAC), the IMRT delivery effects were shown to produce a smearing of the PTV (oesophagus) and an increase of 2-3 Gy in the dose delivered to the spinal cord. For the prostate (and pelvic nodes) tumour site and the CadPlan/Helios, (Varian Medical Systems) an increase of delivered dose of, approximately, 3 Gy was observed for 50% of the total volume of the organs at risk: bladder, rectum and small bowel. In addition to this, an increase of, approximately, 2 Gy was observed in the dose delivered the 50 % of the total volume of the pelvic nodes, the secondary PTV region. The results obtained showed that if delivery effects are not accounted for at the planning/optimisation stage, then an increase in delivered dose to several of the volumes of interest may be expected, after the delivery of the IMRT profiles.

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Figure Captions

Figure 1. The DVH of the optimum (OPT_PTV) or delivered dose to the PTV by (a) 3 and (b) 5 IMRT plans. The delivery techniques represented are the (i) MSF with 2% (red), 5% (blue) and 10% (green) tolerance error for the 3 beam and 5% (blue) and 10% (green) for the 5 beam and the (ii) compensator (orange) for the 5 beam case.

Figure 2. The oesophagus dose distribution obtained from the (a) planning system and delivered with MSF for (b) 2% and (c) 5% tolerance error. The 98%, 80%, 50% and 20% iso-dose levels are respectively, red, green, blue and yellow.

Figure 3. The DVH obtained for the spinal cord in the case of the 3 and 5 beam plans. The delivery techniques represented are the (i) MSF with 2% (red), 5% (blue) and 10% (green) tolerance error for the 3 beam and 5% (blue) and 10% (green) for the 5 beam and the (ii) compensator (orange) for the 5 beam case.

Figure 4. The DVH obtained for the left and right lungs in the case of the 3 and 5 beams IMRT plan.

Table 1:

MEAN DOSE							
“BEFORE” LEAF SEQUENCING							
.	DOSE DELIVERED TO VOLUMES OF INTEREST						
VOL	BLADDER	BOWEL	RECTUM		PTV PROSTATE	RIGHT NODE	LEFT NODE
5%					71.00	53.33	65.33
10%	69.73	41.17	68.00				
25%	62.37	31.50	51.00			50.17	50.50
50%	48.83	24.17	40.83		70.00	48.30	48.30
75%	39.70	13.67	36.10			46.43	46.50
90%	32.07	2.67	31.17				
95%					67.33	43.67	43.83

MEAN DOSE							
“AFTER” LEAF SEQUENCING							
.	DOSE DELIVERED TO VOLUMES OF INTEREST						
VOL	BLADDER	BOWEL	RECTUM		PTV PROSTATE	RIGHT NODE	LEFT NODE
5%					72.28	53.62	63.14
10%	68.24	41.80	66.16				
25%	61.85	33.74	52.46			51.62	51.60
50%	50.98	27.49	43.86		69.77	50.34	49.98
75%	42.59	15.24	39.34			48.90	48.56
90%	35.85	5.73	36.23				
95%					66.36	46.76	46.48

Figure 1:

Figure 2

(a)

(b)

(c)

Figure 3

Figure 4