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NOTE

Estimation of a radiation time prolongation factor for intensity-modulated radiotherapy

A Bakai, M Alber and F Nüsslin

Abteilung für Medizinische Physik, Universitätsklinik für Radioonkologie, Hoppe-Seyler-Str 3, 72076 Tübingen, Germany

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Abstract

In general, the deposition of a given target dose requires a longer radiation time for intensity-modulated photon beams (IMBs) than for unmodulated beams. Hence, the routine use of intensity-modulated radiotherapy (IMRT) has repercussions both on the exposure of the patient to scatter and institutional radiation safety. A rule of thumb is presented to assess the maximum prolongation of radiation time for a case class in an idealized setting using static superimposed field segments. The method considers only the degree to which risk structures have to be blocked to meet specified dose restrictions.

1. Introduction

Intensity-modulated radiotherapy (IMRT) is rapidly being implemented for clinical routine in many hospitals. The price to be paid for its promise of better sparing of organs at risk (OARs) is prolonged irradiation times and an even greater dependence on treatment planning software.

The purpose of this note is to present a simple formula to assess the maximum prolongation of beam-on time for a case class in an idealized setting. This rule of thumb can provide a plausibility check for intensity-modulated treatment plans which may comprise several times as many monitor units (MUs) as conventional treatment plans and hence evade clinical experience.

It can also aid in estimating the whole-body dose originating from leakage and scatter which is proportional to the total number of MUs for a generic class of cases. Further, it can be used to estimate the increased demands on the shielding design for treatment rooms. Similar, yet less detailed, considerations based on practical experience with IMRT were made by the Intensity Modulated Radiation Therapy Collaborative Working Group (2001) and Mutic *et al* (2001). In contrast, the rule presented here allows the making of predictions about the expected radiation time prolongation factor (RTPF) based solely on the dose prescription characteristics for a class of treatment cases.

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2. Method

The delivery of conventional 3D-conformal radiation therapy is typically accomplished with a set of beams shaped using the projection of the planning target volume (PTV). Every point in the PTV is therefore irradiated by approximately the same primary fluence, if we discount differences in radiological depth.

Starting from this premise, consider IMRT as a re-distribution of primary fluence to a number of field segments: from certain beam areas fluence is removed by partial blocking of OARs and applied from other beam incidences in the shape of additional fill-in segments in order to maintain approximately constant primary fluence in every point of the PTV. In other words, we assume that the total photon flux of a given treatment is equivalent for unmodulated and intensity-modulated beams (IMBs). Since any multileaf collimator based application requires the fragmentation of IMBs into multiple segments of smaller area, the integral radiation time has to increase for IMRT.

Let RTPF be the radiation time prolongation factor, defined as the ratio of the number of MUs required for an IMRT treatment divided by the number of MUs required for a conventional treatment:

$$\mathrm{RTPF} = \frac{\mathrm{MU_{IMRT}}}{\mathrm{MU_{conv}}}. \tag{1}$$

Here, as well as below, any MU or dose specification given corresponds to a single fraction. The value of RTPF depends on the degree of fluence modulation of a given treatment plan.

Assume that a given OAR should receive no more than the maximum dose $D_{\max}$, which means the structure should be spared to a degree of

$$s = 1 - \frac{D_{\max}}{D_{\mathrm{presc}}}.$$

D_{presc} in the above equation corresponds to the prescribed target dose.

Figure 1 depicts the situation for a concave PTV and a single OAR located in the path of a conventional beam and an IMB. The fluence distributions of the beams are illustrated as relative MU distributions (rel $\mathrm{MU_{conv}}$, rel $\mathrm{MU_{IMRT}}$) along lines perpendicular to the central beam axis. In the schematic display of the modulated beam, we already assume that on average (over all IMBs), the OAR will be shielded by a factor s. The geometrical configuration, an OAR surrounded on two sides by a PTV, corresponds to the geometrical worst-case situation. In the following, we will assume such a configuration for all beams contributing to an IMRT treatment to arrive at an estimate of the maximum RTPF as a function of the shielding s.

The modulated fluence distribution rel $\mathrm{MU_{IMRT}}$ of figure 1 has to be applied as a hypothetical sequence of $3 + n$ field segments. Segment I, irradiating both PTV and OAR, contributes a fraction $(1 - s)$ to the RTPF and segments II und III, irradiating only the PTV, contribute a factor s each. The missing flux of segment IV has to be contributed by other beams, hence another fraction s has to be added to the total RTPF of this beam. Likewise, this beam compensates for shielding in other beams so that additional n segments would have to be applied from this direction, which are not displayed in figure 1 for the sake of simplicity. However, their contribution has already been taken into account together with those beams from which flux had been taken away.

Hence, the RTPF for a single beam shielding a single OAR is given as

$$\mathrm{RTPF_{beam}} \approx (1 - s) + s + s + s \approx 1 + 2s.$$

If we assume an identical worst-case geometry for each IMB of a complete set, it follows for the total RTPF for the case that a single OAR is considered during planning:

$$\mathrm{RTPF} \approx 1 + 2s.$$

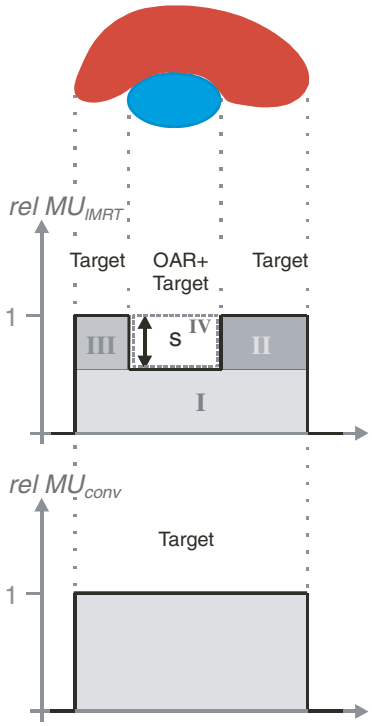

Figure 1. Relative MU distribution for an unmodulated beam and an IMRT beam with identical incidence direction. The IMB is partially blocking a single OAR.

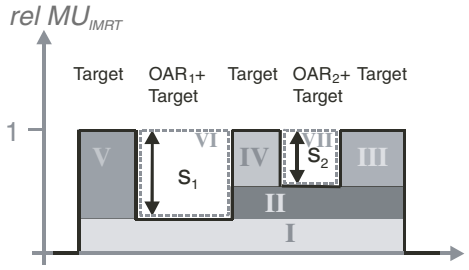

Figure 2. Relative MU distribution of an IMRT beam with two OARs partially blocked.

From figure 2, the approximate RTPF for an arrangement with two OARs and a PTV, aligned in the worst possible way, can be deduced. If the geometrical worst-case situation continues for all beams of an IMRT treatment plan where n OARs are considered, the total RTPF can be obtained as

$$\mathrm{RTPF} = 1 + 2\sum_{k=1}^{n} s_k \tag{2}$$

where

$$s_k = 1 - \frac{D_{\mathrm{max}\_k}}{D_{\mathrm{presc}}} \tag{3}$$

is the degree to which the kth OAR is blocked.

Table 1. Estimated and observed RTPFs for two indications. Further, dose, MU and segment number data are presented. The prostate data are averaged over the treatment plans of ten patients, the H&N data correspond to a single IMRT plan.

	D_{presc}/ fraction (Gy)	OAR $D_{\max}$/ fraction (Gy)		$\text{RTPF}_{\text{predict}}$	$\text{RTPF}_{\text{observ}}$	$\text{MU}_{\text{IMRT\_}H}$	IMRT segment number (beams)
Prostate	2.1	Rectum	1.9	1.2	1.2 ± 0.16	244.4 ± 31.9	20.9 (5)
H&N	2.0	Spinal cord Parotid glands	0 0	5.0	5.0	1004.1	94 (7)

The extension to dose–volume constraints for OARs can be made if it is possible to interpret this as a maximum dose constraint for a partial volume of the OAR. This will often be the case if the OAR is small relative to the target volume and in close vicinity to it, e.g. for the parotids. In case multiple dose–volume constraints are used, or the OAR is of the size of the target volume (e.g. lungs), it is generally hard to predict the shielding requirements. Application of the formula using the lowest dose constraint of the respective OAR will often lead to an overestimation of the RTPF.

Equation (2) is related to the estimate of total treatment time given by Stein *et al* (1994). While the present equation applies to a case class in a setting using static field segments, the estimate of Stein *et al* refers to dynamic multileaf collimation of a single beam.

So far, all considerations were based on a longitudinal symmetry of the treatment situation. If the treatment situation deviates from this symmetry, both a greater or lesser degree of fluence modulation may result, which is difficult to assess in general. Also, limitations of the treatment planning software and delivery equipment may cause a further fragmentation of the fields into segments, hence also leading to an increased RTPF. However, by the assumption of a worst-case geometry, the estimates on the RTPF are rather conservative, so that often solutions with smaller than predicted RTPFs can be encountered.

3. Results

Table 1 summarizes RTPFs for treatments of patients with prostate or H&N tumour. The MUs shown, $\text{MU}_{\text{IMRT\_}H}$, are the results of the planning software Hyperion, an inverse IMRT treatment planning system developed at our department (Alber *et al* 2000). The examples serve the purpose of illustration rather than justification of formula (2), because we cannot claim that the MUs obtained from our treatment planning system are anywhere near the ideal minimum. Hence for prostate, all listed data were averaged over a group of ten patients. Mean values ± 1 standard deviation are listed in the table. In a simple setting such as this, the RTPF estimate is rather accurate.

In contrast, the shielding requirements for this particular H&N treatment resulted in a very complex treatment plan with $\approx$1004 MUs per fraction, a result that can also be made plausible by the consideration made above. The extreme shielding requirements ($D_{\max}$/fraction $= 0$ Gy) for the spinal cord and the parotids in this plan are due to the fact that the patient had undergone prior conventional radiation treatment which had exhausted normal tissue tolerance. Dose volume (DVH) constraints (0 Gy to 50% volume) for the parotids were used to allow the planning system to meet the prescription for the target volume.

4. Discussion

For both indications tested, the RTPF calculated by this heuristic rule gives good order-of-magnitude estimates of the actually observed RTPF. In practice, the overestimation of the

RTPF caused by the assumption of a worst-case geometry for all treatment beams approximately balances the effects of variations of patient geometry and constraints of delivery that lead to an increase of the RTPF beyond the ideal limit. An important role in reducing the practical RTPF is played by the treatment planning software, where inclusion of the segmentation into the optimization proves crucial for inverse (Alber *et al* 2001) and forward (De Gersem *et al* 2001) approaches alike.

The rule cannot estimate the total delivery time because it does not make predictions about the number of segments necessary to deliver a treatment. In fact, predictions of this kind are very case dependent and difficult. Note that the number of segments and the number of MUs are not strictly related. Only this fact makes it possible to formulate such a general rule of thumb for the RTPF at all.

The intention of the presented rule is to provide a comprehensive tool for simple plausibility checks of RTPFs in IMRT while considering the characteristics of the individual dose prescriptions. Since the rule predicts radiation time for an arbitrary treatment setup, it could aid in estimating scatter dose exposure to patients. It is also of interest in facility planning considerations.

Acknowledgments

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