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NOTE

Tumour shapes and fully automated range compensation for heavy charged particle radiotherapy

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Abstract. An idea of computer-controlled range-compensating system for heavy charged particle radiotherapy, the multibar compensator, is proposed. By stacking multiple energy-absorbing layers along the beam, each of which has structure and behaviour similar to those of a multileaf collimator, variable range compensation will be achieved. The analysis of the conventional range compensators actually used for treatment concluded that the proposed system would not seriously degrade the treatment quality for the most cases, except for tumours in head and neck region where 1-mm precision may be required. The system will even be able to coexist with the conventional range compensators to provide either method depending on clinical situations.

1. Introduction

The most advantageous characteristic of heavy charged particle beams for radiotherapy is the sharp falloff at the lateral and distal edges of the beam. For maximum benefit, the beam range should trace the distal surface of the treatment target. However, difficulties in tumour targeting, especially in the presence of organ motions, have been preventing the pencil-beam scanning technique (Kanai *et al* 1980, Pedroni *et al* 1993, Haberer *et al* 1993), from gaining popularity over the broad-beam technique with custom-made range compensators (Wagner 1982).

Advances in computer technology have largely improved and automated the treatment systems. For example, the dynamic multileaf collimation technique has enabled variable and conformal range modulation with broad beams (Futami *et al* 1999). However, range compensation necessary to the broad beams still depends on custom-made compensators. Fabrication and manual handling of the compensators not only are costly and cumbersome for therapists, but also could be a source of unavoidable human errors. This may be the reason why multileaf collimators have become so popular despite the limited field-shaping capability compared with custom-made blocks. In fact, Intensity Modulated Radiation Therapy Collaborative Working Group (2001) discouraged conventional compensators in favour of multileaf collimation techniques for photon intensity modulation.

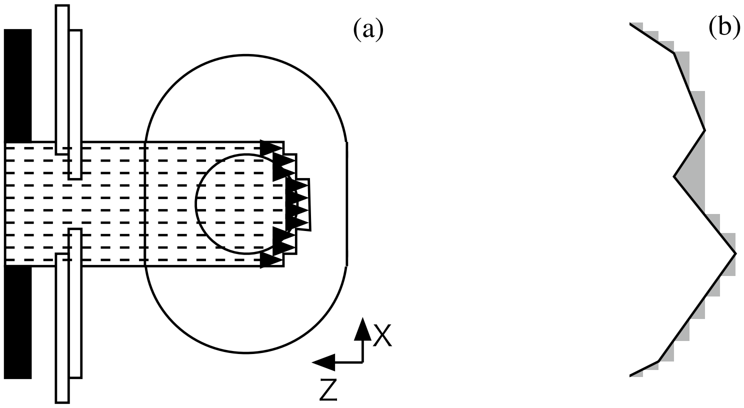

Figure 1. Cross-sectional views of, (*a*) a two-stage multibar compensator attached to a gantry head, a tumour in a patient and the range-compensated beam field, (*b*) distal surface of a target (solid line) and the extra treated volume (grey areas) due to the discreteness and the concaveness.

It will be thus desirable or possibly necessary to establish computer-controlled range compensation in order to truly popularise the heavy charged particle radiotherapy. While, in principle, custom-made compensators can be shaped for perfect range compensation with submillimeter precision, unnecessarily high precision may be compromised for benefit of the fully automated system. In this note, we propose an idea of such a compensating system and discuss its usability with respect to tolerances against degradation of treatment quality, based on the actual patient data.

2. Materials and Methods

Since the shape of the range compensator reflects the shape of the target that is usually round, it will be reasonable to primarily aim only the convex-type range compensation. Figure **??**(*a*) shows the idea of the "multibar" compensator for variable range compensation. The structure is quite similar to that of the multileaf collimator, except that the leaves are thin enough to be better called bars made of light material such as plastic and that they are multistaged in the beam direction. The bars independently inserted in the field absorb the extra beam ranges beyond the target.

Since the bars should have finite dimensions in practice, the achievable range compensation will be discrete resulting in unwanted irradiation beyond the target. In addition, since the adjustments are made by openings of the opposing bars, the normal tissue beyond the concave-shaped target will not be spared in principle. Figure **??**(*b*) shows the unwanted "extra treated volume" beyond the target, which is resulted from both the "discreteness" due to the finite bar dimensions and the "concaveness" of the target.

In order to estimate the conceptual limitation, we studied all the range compensators for carbon-ion beams actually administered for cancer treatment at National Institute of Radiological Sciences in the first semester of fiscal year 2003 as shown in table **??**. We classified the compensators by applied body parts, considering the substantial differences of achievable patient fixation precision, degree of static

Table 1. Numbers of patients and range compensators studied.

Body part	Tumour site	Patients	Compensators
Head and neck	Brain	1	5
	Lacrimal gland	2	6
	not specified	19	84
Chest and upper abdomen	Esophagus	1	2
	Lymph node	1	3
	Lung	19	70
	Liver	12	26
	Pancreas	7	21
	Kidney	1	2
Pelvis and lower abdomen	Bone and soft tissue	28	92
	Prostate	32	138
	Uterus	2	11
	Rectum	8	22

deformation with respect to the planning CT images and degree of respiratory motion.

Since case studies without solid criteria are often inconclusive, we purely looked into range compensation ignoring other clinical circumstances. We analysed the compensator shapes with the thickness matrices designed by the treatment planning system (Endo *et al* 1996). The design was based on simple ray-tracing calculation with 0.6-mm grid spacing averaged within each $3 \times 3\text{-mm}^2$ pixel. The expansion technique by Urie *et al* (1984) against patient misalignment was not applied. Instead, the targets had been expanded keeping the tumour mass density to include margins against misalignment and internal motion.

We first examined the essential limitation of the multibar compensator against the concaveness ignoring practical limitation due to the discreteness. By scanning each row of thickness matrix from both sides toward the bottommost pixel while accumulating differences between the current pixel thickness and the updated minimum per scan, the extra treated volume beyond the target, namely the concave volume, was calculated. This is equivalent to the ideal multibar compensator comprised of infinite number of stages of infinitesimally thin and pixel-sized bars. The bar movement direction was either matrix row or column whichever gave the smaller concave volume for simplicity though the intermediate angles would be available with a rotational mount.

Figure **??** shows the resultant plots showing the target volume and the concave volume. In order to evaluate the significance of the degradation of dose conformity, $4\pi r^2 \times (1\ \text{mm})$ for 1-mm margin around a spherical target with radius r was also plotted as solid lines for reference. While the planning target volume included normal tissue in the superficial region of typically a few millimetre deep for a margin against set up and internal uncertainties, the extra treated volume of normal tissue due to the concaveness usually amounted to below 1-mm margin level, which would be small enough.

In practice, the bars have to have finite dimensions and numbers. We took here, for a reasonable example, a multibar compensator comprised of 10 stages of 30 pairs of bars with dimensions 5 mm in width and 5 mm H_2O in thickness to cover $15 \times 15\text{-cm}^2$ field and 5-cm H_2O range adjustment . With 12.5-cm bar length allowing 5-cm overrun to the other side, the total 600 bars will weigh less than 2 kg. The discreteness of 5 mm due to the bar dimensions will additionally produce bumps of extra treated

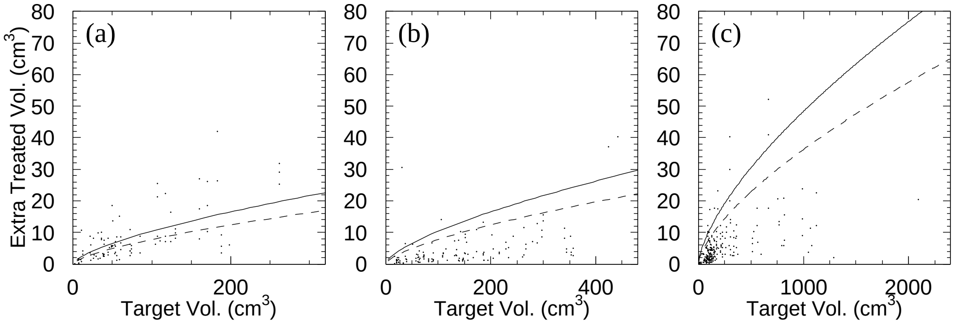

Figure 2. Target volume versus concave volume not compensated with the ideal multibar compensator, (*a*) for head and neck, (*b*) for chest and upper abdomen and (*c*) for pelvis and lower abdomen. The solid and dashed lines indicate the isotropic 1-mm margin volume and distal 3-mm margin volume, respectively, added to a spherical target for reference.

volume, where the mean extra range beyond the target may be 3 mm for a rough estimate. For reference, $\pi r^2 \times (3\text{ mm})$ for the extra treated volume with 3-mm mean extra range was drawn with dashed lines in figure **??**.

3. Discussion

The overall extra treated volume should be a sum of that due to the concaveness and that due to the discreteness, which means that we need to shift the data points on the base of the dashed lines in figure **??**. Then, the extra treated volume would be larger than the 1-mm margin level drawn with the solid lines. In particular, the head and neck tumours tend to require complicated range compensation due to cavities while targeting precision as good as 1 mm may be achievable with a fixation system. The degradation of dose conformity due to the multibar compensator would be thus substantial. On the other hand, if a few-mm margin level of extra treated volume is acceptable, nearly all the tumours in chest, abdomen and pelvis could be treated with the multibar compensator with 5-mm discreteness, where large intrinsic uncertainties inevitably exist in targeting as well (Langen *et al* 2001).

Though the number of bars approaching 1000 is technologically challenging, the setting and verifying control is much less frequent than that for the dynamic multileaf collimation techniques (Intensity Modulated Radiation Therapy Collaborative Working Group 2001) and will be also easier because of the significantly relaxed timing requirement. Also, a structurally similar system was proposed and actually completed for photon beam collimation (Maughan *et al* 1995).

The established mechanical technology for multileaf collimators may be applicable though significant miniaturisation of the actuators must be made since those for multileaf collimators typically weigh several hundred grams per channel. The reduction could hopefully be possible since the weight of a movable element of the multibar compensator will be roughly 1/100 of that of multileaf collimators. Therefore, we are currently investigating this conservative approach to draw a realistic design.

The light weight, if achieved, will enable a detachable multibar compensator in place for the conventional range compensators, allowing either method when necessary. Or, without detaching, the discreteness can be eliminated by adding a thin corrective compensator, which will be easier to fabricate than the conventional range compensators. The treatment planning to determine the bar positions will be straightforward as we have demonstrated with the ideal multibar compensator. The only additional step will be quantisations according to the bar dimensions.

4. Conclusions

A reasonable compromise between quality and cost was pursued for popularisation of heavy-ion radiotherapy. The multibar compensator will offer fully automated treatment systems with sufficient precision for majority of tumours in chest, abdomen and pelvis. On the other hand, there will be substantial degradation of dose conformity for tumours in head and neck.

The multibar compensator will be hopefully constructed and operated with conventional technology though balancing requirements of discreteness, weight, reliability, and cost, in practice must be challenging. By applying either the multibar compensator to the most cases or the conventional range compensators only when necessary with an exchangeable system, the running cost for heavy charged particle radiotherapy will be reduced without sacrificing the quality.

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