Published in final edited form as:

Med Dosim. 2013 ; 38(1): 12–17. doi:10.1016/j.meddos.2012.05.001.

Optimal field-splitting algorithm in intensity-modulated radiotherapy: Evaluations using head-and-neck and female pelvic IMRT cases

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Abstract

To develop an optimal field-splitting algorithm of minimal complexity and verify the algorithm using head-and-neck (H&N) and female pelvic intensity-modulated radiotherapy (IMRT) cases. An optimal field-splitting algorithm was developed in which a large intensity map (IM) was split into multiple sub-IMs (≥ 2). The algorithm reduced the total complexity by minimizing the monitor units (MU) delivered and segment number of each sub-IM. The algorithm was verified through comparison studies with the algorithm as used in a commercial treatment planning system. Seven IMRT, H&N, and female pelvic cancer cases (54 IMs) were analyzed by MU, segment numbers, and dose distributions. The optimal field-splitting algorithm was found to reduce both total MU and the total number of segments. We found on average a $7.9 \pm 11.8\%$ and $9.6 \pm 18.2\%$ reduction in MU and segment numbers for H&N IMRT cases with an $11.9 \pm 17.4\%$ and $11.1 \pm 13.7\%$ reduction for female pelvic cases. The overall percent (absolute) reduction in the numbers of MU and segments were found to be on average $-9.7 \pm 14.6\%$ (-15 ± 25 MU) and $-10.3 \pm 16.3\%$ (-3 ± 5), respectively. In addition, all dose distributions from the optimal field-splitting method showed improved dose distributions. The optimal field-splitting algorithm shows considerable improvements in both total MU and total segment number. The algorithm is expected to be beneficial for the radiotherapy treatment of large-field IMRT.

Keywords

Field-splitting algorithm; Intensity map; Multileaf collimator (MLC); Large-field IMRT

Introduction

Image-guided radiotherapy (IGRT) using intensity-modulated radiotherapy (IMRT) allows clinicians to treat the clinical sites that for many years were treated using conventional 4-field box or 3D conformal techniques. The IGRT technique guards against shifts in the patients' position on fraction-by-fraction bases, allowing the delivery of large fields to avoid

organs-at-risk (OAR) while conformally covering the clinical target volume. This IMRT approach has been explored for cancers of the pelvic region: ovarian cancer¹ cervical cancer,² and pelvic lymph nodal regions for prostate cancer.³ The use of IMRT has shown dosimetric benefits over whole-abdomen radiation by increasing dose on target volumes³ and/or decreasing dose to OAR, bone marrow for example.² However, the large fields needed for IMRT are typically performed by field splitting because of the limitations of current multileaf collimator (MLC) design. IMRT fields wider than 15 cm must be subdivided into subfields when using a Varian linear accelerator (LINAC) (Varian 2100EX series, Varian Associates, Palo Alto, CA). The subfields are delivered separately. However, the field-splitting techniques result in an increase in monitor units (MU) and number of segments. Hong *et al.* reported that delivering 150 cGy using a field-splitting IMRT technique (*i.e.*, dynamic MLC) for ovarian cancer required, on average, 1442 MU, whereas the conventional technique required, on average, 290 MU. There are many studies on field-splitting algorithms,⁴⁻¹⁰ although most^{5,7,8,11} focus on the efficiency of total MU but none of the studies quantified the total segment number improvement.

In this study, we investigate a method in which a large intensity map (IM) is split into multiple sub-IMs subject to the maximum leaf spread and the minimum feathering width constraints while minimizing the total complexity of the resulting sub-IM. Our optimal field-splitting method also strives to minimize the maximum number of MU of those sub-IMs in the resulting split. An efficient algorithm has been developed for solving this field-splitting problem. The optimal field splitting method is even capable of splitting an IM into an arbitrary number of sub-IMs if necessary. A comparison study was conducted on the optimal field-splitting method against one used in a commercial inverse treatment planning system (TPS).

Methods and Materials

Optimal field-splitting algorithm description

Ideally, an IM with a low complexity has a small number of MU. The complexity of an IM is defined as *the sum of positive gradients* (see Appendix). Namely, the complexity of an IM is minimal because it has a more uniform intensity distribution. For large-field IMRT treatment, field splitting is typically required in which an IM is split into 2 or more sub-IMs. However, while splitting an initial IM, the total complexity of the resulting sub-IMs may be increased, thus prolonging the treatment time. The optimal field-splitting method we propose in this study seeks to split an initial IM into sub-IMs, so that: (1) Any 2 neighboring sub-IMs that overlap each other in the resulting split will have a width of the feathering region no smaller than the minimum feathering width (the details of feathering are found in Wu *et al.*⁸); (2) the width of each sub-IM is no larger than the maximum leaf spread that refers the maximum field size with which IMRT is able to be delivered; and (3) the total sum of the complexities of all resulting sub-IMs is minimized. Regarding the feathering of sub-IMs, we perform further optimal decomposition of the feathering regions, yielding a split consisting of the desired number of sub-IMs, so the maximum number of MU of the sub-IMs in the resulting split is minimized, while imposing the lower bound on the total sum of the complexities of the sub-IM in the split. This approach is based on the fact that the

resulting sub-IMs in general have an unbalanced number of MU for delivery. Some sub-IMs may have a much larger number of MUs than others. In this paper, we split an initial IM into the minimum number of sub-IMs needed with balanced MU among sub-IMs. The optimal field splitting method we are proposing is able to process an arbitrary number of sub-IMs needed for a field size >27 cm as used in most typical MLC systems.

Figure 1 shows the basic workflow of the optimal field-splitting method. We first locate the feathering regions whose optimal decomposition leads to an optimal split. A dynamic programming approach¹¹ is used to identify such an “optimal” set of feathering regions whose total complexity increase is minimized (Appendix A). Dynamic programming is a method for solving a complex problem by breaking it down into smaller subproblems. The optimal solution to the original problem contains within it optimal solutions to subproblems (called the *optimal substructure*). One can recursively solve the subproblems and use the solutions to the subproblems to form an optimal solution to the original problem. The method works as follows. First, consider each IM consisting of first columns of the initial IM, whose field size is smaller than maximum IMRT field size; the IM does not need to be split. The total complexity increase of the IM is zero. Then consider every IM consisting of first columns of the initial IM, which need to be split into 2 sub-IMs. We try all possible splitting locations, each of which leads to the column after the splitting location, forming a feasible sub-IM. The total complexity increase is the complexity increase of that sub-IM plus the total complexity increase for the field splitting problem on the rest of the considered IM (*i.e.*, the considered IM – sub-IM) whose optimal solution is known from the previous step of the method. We can find the optimal location to do the splitting for such an IM whose resulting sub-IMs is 2. In general, we consider the initial IM, which needs to be split into multi-sub-IMs. The minimum number of sub-IMs is set as d . Using the same formula as above, we try all possible splitting locations, each of which results in a feasible sub-IM consisting of the column after the splitting location and the rest of the columns before the location that need to be split into $d-1$ sub-IMs. Because the optimal solution to the field-splitting problem on those IMs that need to be split into $d-1$ sub-IMs is already known from the previous step of the method, we can compute the optimal solution to the field splitting problem on the initial IM to be split into d sub-IMs. Then we can compute the optimal split of the initial IM into multi-sub-IMs. The set of resulting feathering regions is finally decomposed in a way to form an optimal split of the initial IM A . The decomposition is modeled as computing a min-max slope path problem in a special monotone polygon¹² (see Appendix B for a detailed description).

Test cases

We verified the performance of the optimal field-splitting algorithm for a total of 54 IMs from 7 patients. Thirty-one IMs were retrospectively studied for 4 head-and-neck (H&N) plans and 23 IMs were retrospectively studied for 3 female-pelvic clinical IMRT plans. All IMRT plans were clinically generated by experienced dosimetrists using the Pinnacle TPS (Philips Healthcare, Andover, MA). Their ideal IMs, *i.e.*, before converting into deliverable IMs and accounting for field size and multileaf thickness, were retrospectively used in this study. The ideal IMs were converted through 2 methods: (1) The optimal field-splitting algorithm and (2) a conventional field-splitting algorithm used by the Pinnacle TPS. For the

purpose of this study, we focused on the algorithm comparisons of field splitting. The algorithm of direct machine parameter optimization (DMPO; Raysearch Laboratories, Stockholm, Sweden) is detailed in the Discussion. The resulting IM from the 2 different algorithms were compared in terms of MU, number of segments, and dose distribution. Seven and 8 equally spaced, nonopposing beams were used for the H&N IMRT plans and the female-pelvic IMRT plans, respectively. All plans used 6-MV photon energy with a step-and-shoot MLC technique on a Varian LINAC equipped with the Millennium MLC. The distance between any 2 leaves on the same bank of an MLC cannot exceed 15 cm, which is the maximum field size. Therefore, when an ideal IM was converted into a deliverable IM, all IMs were split into 2 sub-IMs. The adjacent sub-IM overlapped by a fixed 3 cm to minimize field match errors, with intensity feathering in the overlapping region. The size of the IM was 101×101 beamlets and the maximum intensity levels ranged from 42–147. The sizes of the planning target volume (PTV) were between 15 and 19.5 cm.

The plans from the optimal field-splitting method were compared against the plans generated by the Pinnacle TPS. The total number of MU and segments were compared, as well as the quality of the resulting dose distributions of the field splitting.

Results

Optimal field splitting algorithm evaluation

Figure 2 shows the intensity distribution and simulated film for the original IM and sub-IM. In the feathering region, the intensity change is generally smooth and approximately evenly distributed between the 2 sub-IMs. The increase in the number of MU is small and the IM delivery efficiency of IMRT was optimized.

One of the advantages of the optimal field-splitting algorithm is that you can split a given IM into >2 sub-IMs. Another advantage is that the optimal field-splitting method is globally optimal in terms of our complexity definition: It is free from the risk of local optima. The optimal field-splitting method also showed low polynomial running complexity. On a Pentium-M 2.8-GHz machine with 3.5-GB memory, all field-splitting processes were performed in 1 second.

However, there are potential limitations to the optimal field-splitting method, and further studies are expected to follow. First, the method tended to split the given IM with a large feathering region, trying to reduce the maximum intensity. This runs the potential risk of generating sub-IM with more segments or a greater number of MU than those generated in a conventional plan. This issue can be remedied by setting an upper limit on the width of the feathering region as used in the Pinnacle's splitting scheme. Another potential limitation is that although our objective function design was closely related to the number of MU of a given IM, it cannot guarantee producing a split of an optimal MU efficiency. With regard to the MU efficiency, the resulting splits may even be worse than those produced by the Pinnacle TPS in some cases.

Efficiency evaluation

We found that larger reductions in MU and segment numbers occurred in the female pelvic IMRT cases that had larger field sizes compared with the H&N cases. Of the 3 H&N cases, 31 IMs were tested, showing on average a $7.9 \pm 11.8\%$ reduction in MU numbers and a $9.6 \pm 18.2\%$ reduction in segment numbers (Fig. 3a). For each IM, the improvements in MU and segment numbers were found to be on average -12 ± 23 MU and -2 ± 5 , respectively. The maximum MU and segment reductions were measured as -65 MU and -13 . A total of 20 (65%) and 17 (55%) IMs out of the 31 tested IMs showed the improvements in MU and segment numbers, respectively. The total reductions for all H&N IMRT cases was -94 ± 29 in MU and -18 ± 16 for the number of segments.

For the 3 female pelvic IMRT cases, 23 IMs were tested (cf. Fig. 3b). On average there occurred an $11.9 \pm 17.4\%$ reduction in MU numbers and an $11.1 \pm 13.7\%$ reduction in the number of segments. We found 18 (78%) and 16 (70%) of 23 IMs showed improvements in MU and segment numbers, respectively. For each IM, an average -20 ± 27 reduction in MU occurred and a -3 ± 5 reduction in number of segments occurred. The maximum reduction in MU delivered and number of segments were measured as -89 MU and -14 , respectively. In addition, an average -150 ± 23 MU and -15 ± 10 improvements were found for each female pelvic IMRT case.

For all IMs, the percentage (absolute) reduction in the numbers of MU and segments were found to be on average $-9.7 \pm 14.6\%$ (-15 ± 25 MU) and $-10.3 \pm 16.3\%$ (-3 ± 5), respectively. A total of 39 IMs of 54 tested IMs (72%) showed improvement in the number of MU, whereas 33 (61%) had a reduction in segment number.

The improvements in efficiency we found are considered a result of the global optimization of the complexity function and freedom on the choice of feathering region. Balancing the number of MU is also expected to contribute to the improvements in efficiency.

Clinical considerations

The dose distributions from the optimal field-splitting method showed a more favorable result than those from the Pinnacle TPS, along with a reduction in the number of MU and number of segments. Figure 4 shows a dose distribution comparison of 1 case of each of the H&N and pelvic IMRT patients. As seen in Fig. 4b and 4d, the dose-volume histograms (DVHs) of all the PTVs using the optimal field-splitting method showed better PTV coverage regardless of the type of case: H&N or pelvic IMRT. However, this superior PTV coverage was more pronounced on the more complex (H&N) IM case. In relation to OAR sparing, the DVHs from the optimal field-splitting method also showed more favorable dose distributions than those from the Pinnacle TPS, regardless of the case. The improvement in dose distribution for the optimal field-splitting method was confirmed by comparing the isodose lines of the plans, as seen in Fig. 4a and 4c. In all 7 patient cases, we confirmed that the optimal field-splitting method improved the numbers of MU and segments while improving, at least without compromising, the dose distributions after the field-splitting process.

When splitting a large IM into smaller sub-IMs, the goal is to achieve the split as efficiently as possible. Two indexes, the number of MU and the number of segments, are associated with the delivery efficiency of an IM. One can use either one to measure the complexity of an IM and to minimize the total complexity of the sub-IM of a split. This method presents 2 challenges. First, the resulting optimization problem took a prohibitively long time to compute the splitting result for a relatively large-intensity field. Second, minimizing the total number of either MU or segments resulted in a split of compromised quality compared with other methods. Previous studies^{5,7,8,11} mainly focused on reducing the total MU delivered in a split while ignoring the total number of segments. Here, we use the sum of positive gradients to measure the complexity of an IM, which is closely related to the number of MU. The comparison studies, however, revealed that the total segment efficiency is improved with our methods compared with the field-splitting method used by the Pinnacle TPS.

Our comparative focus was between the field-splitting algorithm and a conventional algorithm as used in the Pinnacle TPS. However, to discuss the implications of our optimal field-splitting algorithm in the context of DMPO, we also compared our method with DMPO. All IMRT plans were re-optimized with the selection of the DMPO optimization method without any change of optimization parameters. A further reduction in the number of MU was founded when the DMPO algorithm was applied. This returned a normalized 3% reduction of MU in DMPO. The reason for this reduction is that it included an optimization process that we initially excluded for the purposes of this study, developing an optimal field-splitting algorithm. However, it is noted that for the complex IM cases, *i.e.*, H&N IMRT, we found our optimal field-splitting algorithm showed better data against DMPO—on average –43% MU reductions for 45% IM cases (14/31).

In all the cases we tested, all IMs were split into 2 fields. However, as reported by Hong *et al.*¹ in their IMRT study for ovarian cancer, field sizes wider than 27 cm do occur and the field must be split into 3 subfields. The optimal field-splitting method is not constrained by the number of fields it can split and is easily capable of effectively splitting an IM into multiple sub-IMs. As IMRT is applied to the treatment of more sites requiring large fields, the optimal field-splitting method has the potential to improve the quality of IMRT delivery by considerably reducing the number of MU and segments required.

Conclusions

The use of IMRT to treat large fields is increasing, sometimes requiring the field to be split because of the constraints imposed by the treatment devices. The optimal field-splitting method we propose for large-field IMRT is able to both reduce the number of MU and the number of segments required. The algorithm is globally optimal with respect to its given complexity. The percentage reductions (absolute) in the number of MU and segments needed were found to be on average –9.7% (–15 MU) and –10.3% (–3) for H&N and female pelvic IMRT cases, respectively. The improved IMRT delivery efficiency from the optimal field-splitting method is expected to be beneficial for the IMRT treatment requiring large fields.

Acknowledgments

This work was supported in part by NSF grants CCF-0830402 and CCF-0844765, and the NIH grant K25-CA123112.

Appendix

In this appendix, we present the methods of computing the optimal set of feathering regions and balancing the number of MU of each sub-IM. Given an initial $A = (a_{i,j})_{m \times n}$ IM of size $m \times n$, we use a measure related to the *sum of positive gradients* to compute the complexity

$C(a)$ of A , more precisely, $C(A) = \sum_{i=1}^m \left(a_{i,1} + \sum_{j=2}^n \max(0, a_{i,j} - a_{i,j-1}) \right)$, where m, n refer the size of initial IM A (i.e., $m \times n$) and $a_{i,j}$ is the intensity level of the bixel (i, j) . We want to split A into $d = \lceil n - \delta / w - \delta \rceil$ sub-IMs, which is the minimum number of sub-IMs needed, and n, δ, w refer to the size of each row of the initial IM, the minimum width of the feathering regions, and the minimum leaf spread, respectively.

A. Computing the optimal set of feathering regions

We first show how to compute the minimum increase of complexity for a given feathering region and then present the method for computing the optimal set of $(d-1)$ feathering regions using dynamic programming.¹¹ Here, d is again the minimum number of sub-IMs that typically number 2 or 3 in clinical large-field IMRT. A key observation is that to find an optimal split of d sub-IMs while minimizing the total complexity is the equivalent to finding $(d-1)$ feathering regions whose total increase of the complexity is minimized. The problem is solved using dynamic programming.¹¹

To establish a computation base for dynamic programming, we demonstrate how to compute the minimum increase of the complexity while decomposing a feathering region. When decomposing a feathering region, the increase of complexity is the sum of the complexities of the resulting 2 sub-IMs less the complexity of the original IM before splitting. After we mathematically studied this problem, we found that the increase of complexity depends totally on the feathering region—actually, an extended feathering region, which is the feathering region plus 1 column to the left and 1 column to the right. A linear time algorithm^{11,12} exists for computing the minimum complexity increase when decomposing a feathering region. Given a feathering region of $F = (f_{i,j})_{m \times N}$ m rows and N columns, we denote the extended feathering region by $F_{ext} = (f_{i,j})$, $i = 1, \dots, m$, and $j = 0, \dots, N+1$. The

sum of positive gradients of each row i of F_{ext} is defined as $\sum_{j=1}^{N+1} \max(0, f_{i,j} - f_{i,j-1})$. From the work of Chen *et al.*⁵ and Wu *et al.*,¹² we know that the minimum row complexity increase for each row i equals to either 0 or $f_{i,N+1}$ minus its sum of the positive gradients, depending on which one is larger. Then the *minimum increase* $cpl(F)$ of the complexity for F is the total sum of the minimum row complexity increases of all rows of F .

To apply the dynamic programming approach, we explore the optimal substructure of the problem as follows. Consider the subproblem $P_s(x, N, L, k)$ in which the IM to be split into k sub-IMs consists of the first x columns of the initial IM A ; the first $(k-1)$ sub-IMs cover the

first $(x-N)$ columns of the initial IM A ; and the width of the feathering region between the last two sub-IMs (*i.e.*, the $(k-1)$ -st and k th sub-IM) is L . Denote by $C(x, N, L, k)$ the minimum complexity increase of the subproblem $P_s(x, N, L, k)$. To solve the subproblem $P_s(x, N, L, k)$, in dynamic programming, we solve all possible subproblems in which the intensity map consists of the first $x-N$ columns of A and is to be split into $k-1$ sub-IMs. That is, for any N' and L' with $(N' + L')$ no larger than the minimum leaf spread w , L' no less than the minimum feathering width, and N' no less than L , we need to solve the subproblem $P_s(x-N, N', L', k-1)$ and the minimum increase of the complexity of the resulting feathering region between the $(k-1)$ -st and the k th sub-IMs. The solution to the subproblem $P_s(x-N, N, L, k-1)$ for which the minimum complexity increase of the subproblem plus the minimum complexity increase of the resulting feathering region between the $(k-1)$ -st and the k th sub-IMs is minimized, is used in the solution to the larger subproblem $P_s(x, N, L, k)$. Hence, we can recursively solve the subproblem $P_s(x, N, L, k)$. Initially, if $n \leq w$, we do not need to split A . Thus, for any $x \leq w$, we have $C(x, N, L, 1) = 0$ for any $N + L \leq w$ and. In addition, we need to ensure that the number of sub-IMs in the split is d . Intuitively, after using d sub-IM to split IM A , if the residual IM of A is not empty (*i.e.*, $x > 0$), that means we have to use more than d sub-IM in that split. We thus let to $C(x, N, L, 0) = +\infty$ prevent using more than d

$$\min_{N+L \leq w} \left\{ C(n, N, L', d) \right\}$$

sub-IM for split A . Eventually, the optimal solution to $L \geq \delta$ gives an optimal split of A .

B. Balancing MU of sub-IMs

After obtaining an optimal set of feathering regions $\{F_k | k = 1, 2, \dots, d-1\}$, we can decompose each feathering region F_k , yielding an optimal split of IM A with d sub-IMs, whose total sum of the complexity is minimized. However, some of the resulting sub-IMs may have too many MUs. In this section, we present a linear time algorithm to decompose the optimal set of $(d-1)$ feathering regions to form an optimal split of A so the maximum number of MUs of the sub-IMs in the split is minimized. This decomposition can be performed row by row.

A further study of the feathering region decomposition problem in *Optimal field-splitting algorithm description* reveals the following property^{5,12}: For 1 row of an extended feathering region $b = (b_1, b_2, \dots, b_N)$, there may exist multiple decompositions of b , yielding the minimum complexity increase. We thus have the freedom to distribute the complexity between the 2 resulting vectors of the decomposition. Actually for any non-negative integer $0 \leq \tau \leq \sum_{i=2}^N \max(0, b_i, b_{i-1}) - b_N$, there exists an optimal decomposition $b = x + y$, with of the MU increase distributed to the left sub-IM and the decomposition can be done in linear time.¹²

This enables us to balance the number of MU of the resulting sub-IMs. Given an optimal set of feathering regions $\{F_k | k = 1, 2, \dots, d-1\}$, we aim to decompose those feathering regions to achieve a set S of d sub-IMs $\{S_1, S_2, \dots, S_d\}$, so the maximum $\mu(S)$ of all the MU of those sub-IMs in S is minimized, while imposing the lower bound on total complexity of the split.

We can formulate this problem as computing a polygonal path in a polygon, so that the maximum slope of the segments on the path is minimized, which can be solved in linear time.¹²

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Fig. 1.

Basic flow chart for the optimal field-splitting method, demonstrating the procedure from a large IM to an optimal sub-IM. The minimum increase in complexity for a given feathering region is used. The actual decomposition is performed striving to balance the number of MU.

Fig. 2.

Intensity profiles for the original and split fields. (a) Profile and simulated film for the original large IM. (b) Profile and simulated film for the left IM. (c) Profile and simulated film for the right IM.

Fig. 3.

The comparison of percentage reductions in total MU and total segment numbers between a conventional method in the Pinnacle TPS and the optimal field-splitting method. (a) H&N IMRT case. (b) Female pelvic IMRT case.

Fig. 4.

The comparison of dose distributions in terms of DVH and isodose lines for H&N IMRT case in the upper row (a) and (b) and female pelvic in the lower row (c) and (d). The optimal field-splitting method of solid lines in DVH (b) and (d) showed better dose distributions than Pinnacle (*dashed lines*) in DVH without compromising the isodose lines (see right panels in (a) and (c)).