A Comparison of Step-and-Shoot Leaf Sequencing Algorithms that Eliminate Tongue-and-Groove Effect

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Abstract. The performances of three recently published leaf sequencing algorithms for step-and-shoot intensity-modulated radiation therapy delivery that eliminate tongue-and-groove underdosage are evaluated. Proofs are given to show that the algorithm of Que *et al* (2004) generates leaf sequences free of tongue-and-groove underdosage and interdigitation. However, the total beam-on times could be up to n times those of the sequences generated by the algorithms of Kamath *et al* (2004), which are optimal in beam-on time for unidirectional leaf movement under the same constraints, where n is the total number of involved leaf pairs. Using 19 clinical fluence matrices and 100,000 randomly generated 15×15 matrices, the average monitor units and number of segments of the leaf sequences generated using the algorithm of Que *et al* (2004) are about 2 to 4 times those generated by the algorithm of Kamath *et al* (2004).

Submitted to: *Phys. Med. Biol.*

1. Introduction

The use of multileaf collimators (MLC) for intensity modulated radiation therapy (IMRT) has seen a considerable surge during the last few years. There are several commercially available MLCs that deliver IMRT using segmental multileaf collimation (SMLC) as well as dynamic multileaf collimation (DMLC). In SMLC the beam is switched off while the leaves are in motion. In other words the delivery is done using multiple static segments or leaf settings. This method is also frequently referred to as the 'step and shoot' or 'stop and shoot' method. In DMLC the beam is on while the leaves are in motion. The beam is switched on at the start of treatment and is switched off only at the end of treatment.

In most commercially available MLCs, there is a tongue-and-groove arrangement at the interface between adjacent leaves. In SMLC and DMLC, this tongue-and-groove arrangement results in undedosage of as much as 10-25% along the overlap area of adjacent leaves (Galvin *et al* 1993a, b, Chui *et al* 1994, Mohan 1995, Wang *et al* 1996, Sykes and Williams 1998). Deng *et al* (2001) have argued, based on experiments using a Varian MLC, that for a multiple (≥ 5) field IMRT plan, the tongue-and-groove effect on the IMRT dose distribution is clinically insignificant due to the smearing effect of different fields. However, the effect could be clinically significant for small number of fields and for patient setup with minimal uncertainty. Several algorithms have been proposed to reduce or eliminate the tongue-and-groove underdosage (van Santvoort and Heijmen 1996, Convery and Webb 1998, Dirkx *et al* 1998, Xia and Verhey 1998, Kamath *et al* 2004, Que *et al* 2004). The algorithm of van Santvoort and Heijmen (1996) eliminates the tongue-and-groove effects for DMLC treatment plans. Their work was extended by Webb *et al* (1997) to also account for transmission through an exposed stair-step by partial synchronization of leaves.

Recently three algorithms to eliminate tongue-and-groove effects in step and shoot delivery have been proposed (Kamath *et al* 2004, Que *et al* 2004). One of the two algorithms of Kamath *et al* (2004) eliminates tongue-and-groove effect and interdigitation while minimizing therapy time (beam-on time) for unidirectional schedules. The second eliminates tongue-and-groove effect and minimizes therapy time for unidirectional schedules but does not eliminate interdigitation. Consequently, the therapy time is usually less using the second algorithm. The algorithm of Que *et al* (2004) is designed to eliminate tongue-and-groove effect. Although this algorithm eliminates tongue-and-groove effect on all 1000 random matrices tried in Que *et al* (2004), no proof that the algorithm eliminates tongue-and-groove effect on all possible matrices has been provided. Further, it is not known whether or not the algorithm of Que *et al* (2004) minimizes therapy time. In Section 2 we analyze the algorithm of Que *et al* (2004) and show that it is always successful in eliminating tongue-and-groove effect; the generated leaf sequence is also free of interdigitation. However, the therapy time of the generated leaf sequences may be up to n times that for an optimal leaf sequence free of tongue-and-groove effect and interdigitation, where n is the number of involved leaf pairs. In Section 3, we present a comparison of the relative performance of the tongue-and-groove effect and interdigitation elimination algorithms of Kamath *et al* (2004) and Que *et al* (2004). Our experiments with clinical matrices show that the leaf sequences obtained using the algorithm of Que *et al* (2004) have a therapy time that is between 2 and 4 times that of those obatined using the algorithms of Kamath *et al* (2004). We also experimented with 100,000 random 15×15 matrices as was done by Que *et al* (2004). On these random matrices the algorithm of Que *et al* (2004) generated leaf sequences with a therapy time about 2.5 times that of the leaf sequences generated by the algorithms of Kamath *et al* (2004). The model used here is the same as that used in Kamath *et al* (2003) and Kamath *et al* (2004) and the reader is referred to these papers for fundamental definitions and algorithms.

2. Analysis of the Algorithm of Que *et al* (2004)

In this section we analyze the algorithm of Que *et al* (2004). They use the 'sliding window' method proposed by Bortfeld *et al* (1994) to generate a tentative segment. They then search through the right leaf positions to determine the leftmost right leaf position and position all right leaves at that position. This defines the first segment of the leaf sequence. The residual intensity matrix is calculated and the process is repeated. To obtain the 'sliding window' leaf sequence for each leaf pair, horizontal lines are drawn at unit intensity levels to intersect the intensity profile for that leaf pair. The left and right leaf positions are determined from these intersections and are sorted from left to right to give the final unidirectional leaf sequence. The process is repeated for all leaf pairs. For the case where the intensity levels in the map generated by the optimizer are integers, it is possible to show that the algorithms of Ma *et al* (1998) and Kamath *et al* (2003) (Algorithms SINGLEPAIR and MULTIPAIR for one and multiple leaf pairs respectively) will yield the same leaf sequence as that obtained using the 'sliding window' method of Bortfeld *et al* (1994).

Note that the discrete intensity profile that needs to be delivered, I, is output from the optimizer. Let n be the number of leaf pairs and m be the number of sample points for each leaf pair (i.e., for each row of the profile). We denote the rows of I by $I_1, I_2, \ldots I_n$. Let $I_t(x_i)$ denote the number of MUs that need to be delivered at sample point i (ith column) of leaf pair t (tth row).

Lemma 1 *The algorithm of Que et al (2004) generates unidirectional schedules.*

Proof: During each iteration, the next segment generated using the 'sliding window' method is such that the left leaves are positioned at the leftmost non-zero sample point (i.e., the least i such that $I_t(x_i) > I_t(x_{i-1})$, where $I_t(x_{-1}) = 0$) for each row t in the residual matrix I. The right leaves are positioned at the first columns of the respective rows where there is a decrease in intensity profile (i.e., the least j for which $I_t(x_j) < I_t(x_{j-1})$). For example, for the single row intensity profile of Figure 1, the left leaf will be positioned at x_2 and the right leaf will be positioned at x_6. The algorithm of Que *et al* (2004) repositions all right leaves to the position of the leftmost right leaf thus obtained. During the delivery of this segment, the intensity values in the matrix in the exposed areas decreases, while the other values remain unaltered. Therefore in the new residual matrix, the leftmost non-zero points of rows either remain at the same positions as in the residual matrix of the previous iteration (or the original intensity matrix for the first iteration) or they move to the right. So the left leaves cannot move to the left between successive segments. It is also easy to verify that there can be no index k such that in the updated residual intensity matrix x_k is to the left of the column of right leaf positions in the segment and $I_t(x_k) < I_t(x_{k-1})$ for some row. It follows that the right leaves cannot move to the left either. So the leaf movements are unidirectional and from left to right. ■

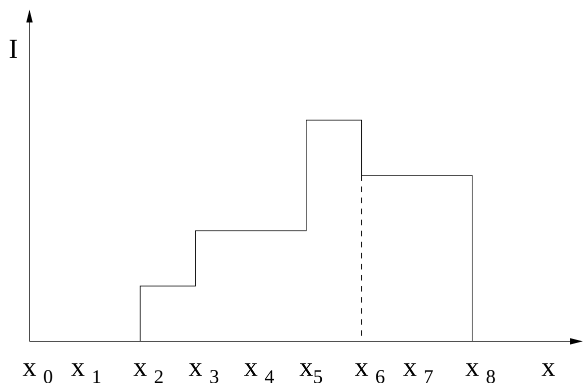

Figure 1. The left leaf will be positioned at x_2, i.e., it will shield x_0 and x_1. The right leaf will be positioned at x_6 and will shield x_i, $i \geq 6$.

Theorem 1 *The algorithm of Que et al (2004) generates schedules free of tongue-and-groove effect and interdigitation.*

Proof: Let $I'_{tl}(x_i)$ and $I'_{tr}(x_i)$, respectively, be the number of MUs delivered when the left and right leaves of pair t pass x_i in the schedule generated by the algorithm of Que *et al* (2004). In the schedule generated, all right leaves pass point x_i, $0 \leq i \leq m$ (during their left to right momement) after exactly the same number of monitor units (MUs) are delivered. So $I'_{tr}(x_i) = I'_{(t+1)r}(x_i)$, $0 \leq i \leq m$, $1 \leq t < n$. From this equality, Lemma 1, Definition 1 of Kamath *et al* (2004), and Lemmas 3 and 4 of Kamath *et al* (2004), it follows that the schedule generated by the algorithm of Que *et al* (2004) is free of tongue-and-groove effect and interdigitation. ■

Theorem 2 *Let T_{tng-id} be the optimal therapy time unidirectional leaf sequence that delivers an intensity profile I, while eliminating the tongue-and-groove effect and interdigitation. The therapy time for the schedule generated by the algorithm of Que et al (2004) is at most $n * T_{tng-id}$, where n is the number of involved leaf pairs. Further, $n * T_{tng-id}$ is a tight bound, i.e., there exist profiles I for which the schedule generated by the algorithm of Que et al (2004) requires a therapy time of $n * T_{tng-id}$.*

Proof: Let $\Delta_{jr}(x_i)$ denote the amount of therapy time for which the right leaf of leaf pair j stops at x_i in the schedule obtained for I using Algorithm MULTIPAIR (Kamath *et al* 2003). The therapy time for the plan of leaf pair j is the sum of times for which its right leaf stops at all sample points, which is $\sum_{i=0}^{m} \Delta_{jr}(x_i)$. The therapy time of the entire schedule, T, is the maximum of the therapy times of all leaf pairs, i.e., $T = \max_j\{\sum_{i=0}^{m} \Delta_{jr}(x_i)\}$. Clearly, $T_{tng-id} \geq T$. In the schedule generated by the algorithm of Que *et al* (2004), all the right leaves stop at each x_i for the same amount of time, say $\Delta'_r(x_i)$, which is equal to the maximum of the times for which a right leaf stops at x_i in the schedule generated by Algorithm MULTIPAIR, i.e., $\Delta'_r(x_i) = \max_j\{\Delta_{jr}(x_i)\}$. The therapy time for the schedule generated by the algorithm of Que *et al* (2004) is therefore $T'_{tng-id} = \sum_{i=0}^{m} \Delta'_r(x_i) = \sum_{i=0}^{m} \max_j\{\Delta_{jr}(x_i)\}$. Since each $\Delta_{jr}(x_i)$, $0 \leq i \leq m$, $1 \leq j < n$ can contribute a term to this expression for T'_{tng-id} at most once, $T'_{tng-id} \leq \sum_{j=1}^{n} \sum_{i=0}^{m} \Delta_{jr}(x_i) \leq n * \max_j\{\sum_{i=0}^{m} \Delta_{jr}(x_i)\} = n * T \leq n * T_{tng-id}$. Note that the algorithm of Kamath *et al* (2004) generates schedules that are optimal in therapy time for unidirectional schedules. Hence the algorithm of Que *et al* (2004) may generate schedules requiring upto n times the therapy time required by the schedules generated by the algorithm of Kamath *et al* (2004).

The above analysis assumes that leaf pairs are allowed to close within the field as defined by the collimator jaws. This is true for certain designs of MLCs. For MLCs with rounded leaf-end design, significant radiation transmission through the closed leaf pairs requires them to be moved under the collimator jaws. In this case, both the algorithms of Kamath *et al* (2004) and Que *et al* (2004) violate the interdigitation constraint, and only tongue and groove effect is eliminated.

Figure 2 shows an intensity map with 4 rows for which the algorithm of Que *et al* (2004) requires $4 * 20 = 80$ MUs. The map can be delivered using 20 MUs without violating the tongue-and-groove constraint and interdigitation constraint using Algorithm TONGUEANDGROOVE-ID (Kamath *et al* 2004). The example can be generalized for n rows. ■

20	0	0	0
0	20	0	0
0	0	20	0
0	0	0	20

Figure 2. This intensity map can be delivered using 20 MUs using Algorithm TONGUEANDGROOVE-ID (Kamath *et al* 2004). The algorithm of Que *et al* (2004) delivers this map using 80 MUs.

3. Results

We implemented Algorithms TONGUENADGROOVE and TONGUEANDGROOVE-ID (Kamath *et al* 2004) and the algorithm of Que *et al* (2004). For performance comparison, we used two separate data sets. The first set consisted of three clinical IMRT plans with 7, 5 and 7 beams, respectively. The first two plans had a 20% fluence step and last plan had a 10% fluence step. Table 1 gives the total MUs and number of segments required for each of the 19 beams in the 3 clinical plans. On our clinical data set, the algorithm of Que *et al* (2004) generated schedules with 2-4 times as many MUs and segments as did the algorithms of Kamath *et al* (2004). The second data set consisted of 100,000 randomly generated 15×15 matrices. The intensity values in these matrices were random integers from 0 to 10. The average MUs and segments for schedules generated using the three algorithms for this set are shown in Table 2. On this set, the algorithm of Que *et al* (2004) generated schedules with about 2.5 times as many MUs and segments as did the algorithms of Kamath *et al* (2004). Note that in both cases the number of MUs and segments in the schedules generated using Algorithm TONGUEANDGROOVE-ID (Kamath *et al* 2004) are only slightly greater than in those generated using Algorithm TONGUEANDGROOVE (Kamath *et al* 2004).

Beam number	A		B		C	
	MUs	Segments	MUs	Segments	MUs	Segments
1	780	38	280	14	280	14
2	520	26	200	10	220	11
3	760	33	300	15	320	16
4	840	40	420	21	420	21
5	740	32	280	14	280	14
6	780	34	260	13	280	14
7	640	29	260	11	280	11
8	1500	74	380	19	420	21
9	860	43	240	12	240	12
10	1500	67	420	20	420	20
11	1660	78	420	21	440	22
12	840	39	280	14	280	14
13	880	78	280	25	280	24
14	1080	102	300	30	340	33
15	1070	90	310	27	320	26
16	1000	90	340	31	390	36
17	890	71	340	29	340	28
18	990	75	310	29	310	30
19	1010	84	330	30	330	30

Table 1. Number of MUs and segments generated for 19 clinical intensity modulated beams from 3 IMRT plans using algorithms A (Algorithm of Que *et al* 2004), B (Algorithm TONGUEANDGROOVE (Kamath *et al* 2004)) and C (Algorithm TONGUEANDGROOVE-ID (Kamath *et al* 2004)). Beams 1-12 have a 20% fluence step, while beams 13-19 have a 10% fluence step.

A		B		C	
MUs	Segments	MUs	Segments	MUs	Segments
114.3	111.6	47.5	45.7	48.2	46.4

Table 2. Average number of MUs and segments generated over a set of 100,000 random 15×15 matrices using algorithms A (Algorithm of Que *et al* 2004), B (Algorithm TONGUEANDGROOVE (Kamath *et al* 2004)) and C (Algorithm TONGUEANDGROOVE-ID (Kamath *et al* 2004)). The intensity values in the matrices were randomly generated integers from 0 to 10.

4. Conclusion

We have compared three recently published leaf sequencing algorithms that were designed to generate leaf sequences that eliminate tongue-and-groove effect in SMLC. Kamath *et al* (2004) showed that their algorithms (Algorithm TONGUEANDGROOVE and Algorithm TONGUEANDGROOVE-ID) generate schedules free of tongue-and-groove effect. Algorithm TONGUEANDGROOVE-ID also generates schedules free of interdigitation. We have proved that the algorithm of Que *et al* (2004) generates schedules that are free of the tongue-and-groove effect and interdigitation. Our analysis shows that the algorithm of Que *et al* generates schedules that may require upto n times the therapy time required by that for an optimal leaf sequence free of tongue-and-groove effect and interdigitation, where n is the number of involved leaf pairs. In experiments with clinical and randomly generated data sets we find that the algorithm of Que *et al* (2004) generates schedules that require 2 to 4 times the therapy time required by the schedules generated by the algorithms of Kamath *et al* (2004). Since our clinical data sets involved about 10-15 leaf pairs, it follows from Theorem 2 that the algorithm of Que *et al* (2004) could generate schedules requiring as much as 15 times the therapy time required by the schedules generated by the algorithm of Kamath *et al* (2004).

Acknowledgments

This work was supported, in part, by the National Library of Medicine under grant LM06659-03.

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