

Minimising IMRT treatment time by optimal configuration of multileaf collimators

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Abstract

Radiation therapy is the most important treatment for cancer patients. In recent years, multileaf collimators have allowed for more complex radiation plans with the ability to provide better treatments for cancer patients. The multileaf beam head is discretised into channels with a pair of leaves. It can be adjusted to give different configurations to change the distribution of the radiation.

This project investigates the configuration of the leaf positions of multileaf collimator in order to minimise the total treatment time. An integer variable is used for each leaf to describe its position. These integer variables together describe the intensity distribution. Integer programming is used to model the problem; linear relaxation and column generation is then used to solve the problem.

1 Introduction

1.1 Cancer and Radiation Therapy

Cancer is one of the leading causes of death, responsible for around 6.2 million deaths per year globally (WHO, 1998) and is the major focus of the developed countries research. Half of all cancer patients are treated either with radiation alone or in combination with other conventional cancer therapies: surgery, chemotherapy, or biological therapy (National Institutes of Health). Radiation therapy is available for patients with a localised tumour; that is a tumour with unformed metastases, which contained within a certain region of the body. In radiation therapy, radiation is used to destroy the tumour while causing minimal damage to the healthy organs around the tumour.

In the field of radiation therapy, much research is aimed at improving the method of applying the radiation. In recent years with greater computing power, new treatment machines have been developed that provide considerably more complex control.

There are three main methods being implemented clinically to deliver these fields. The beam intensities are modulated using intensity modulators ([S.X. Chang, T.J. Cullip and K.M. Deschesne, 2000], [S.B. Jiang and K.M. Ayyangar, 1998]), binary beam modulators ([M.P. Carol, Peacock: 1995], [S.Y. Woo, W.H. Grant, D. Bellezza et al.,

1996]) and multileaf collimators ([T.R. Bortfeld, D.L. Kahler, T.J. Waldron and A.L. 1994], [S.V. Spirou and C.S. Chui, 1994], [C.X. Yu, 1995]).

A medical linear accelerator (see Figure 1) is used to perform the external radiation treatment. The patient is positioned and fixed on the treatment couch while the beam head rotates into the optimal position for the application of the radiation to the tumour.



Figure 1: *A medical linear accelerator with a beam head and a treatment couch*

1.2 Multileaf Collimator

In recent years, multileaf collimators (MLC) have allowed for more complex radiation plans with the ability to provide better treatments for cancer patients.

The multileaf collimator is part of a linear accelerator. The multileaf beam head is discretised into channels with two banks of leaves; a left leaf and a right leaf. The leaves can be driven independently of each other by microprocessors. The movement of the leaves is limited to one dimension, either in or out. Therefore it can be adjusted in to different configurations to shape the distribution of the radiation. (See Figure 2).



Figure 2: *Leaf pairs of multileaf collimator. Radiation will pass through the open area.*

The initial application of the MLC is the replacement of the cerrobend blocks as a beam-shaping device for the uniform radiation linear accelerator. MLC can also modulate the beam intensity within a field by controlling dwelling times and movement of the leaves or by the superimposing of several sub fields. (Cheng B. Saw Ph.D. a, R. Alfredo C. Siochi Ph.D.b, Komanduri M. Ayyangar Ph.D.a, Weining Zhen M.D.a and Charles A. Enke M.D.a 2001)

The two methods of using MLC are dynamic (shoot while the leaves are moving) and static (stop and shoot). The "stop and shoot" method of producing intensity modulation using combinations of static multileaf collimator segments has a number of advantages. In particular, precise dose delivery (less leaf positioning errors due to the

less complex nature), easy verification, and general availability however it has longer treatment times than dynamic (moving leaf) techniques.

This project investigates the configurations of the leaf positions of multileaf collimator using the “stop and shoot” method. The aim is to minimise the total treatment time; the total beam-on time and the total set-up time.

2 Modulating Treatment Using Multileaf Collimator

2.1 Intensity Profile of the Target Region

Once radiation therapy has been decided as the cancer treatment, the intensity map of the amount of radiation required at each stop and in each section will be determined. An intensity map is a Beam's eye view projections of the planning target volume and the organs at risk. The intensity map is formatted into matrix cells (bixels) due to the width of the leaves on the multileaf collimator. (See Figure 3). The target region is therefore discretised into appropriately sized cells (voxels).

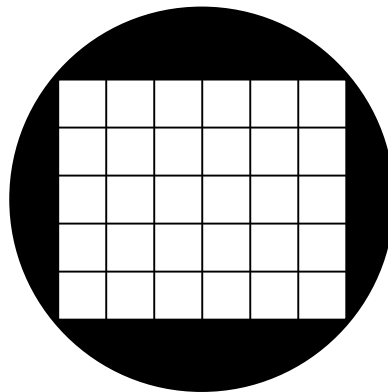


Figure 3: *Beam's eye view of the discretised area when all leaves are totally retracted. Areas coloured in black will always be blocked.*

It is necessary to convert beam profiles into a series of instructions that the multileaf collimator control system can execute. This requires the determination of the appropriate multileaf collimator settings to deliver an intensity map. An intensity map could be written as an intensity matrix, I . The intensity matrix, I , is assumed to be a given $m \times n$ matrix with integer values in each entry. For example, the intensity map of the discretised target region, which will be treated using the beam head shown in Figure 3, could be written as a 5×6 intensity matrix,

$$I = \begin{pmatrix} 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 2 & 3 & 3 & 1 \\ 1 & 2 & 4 & 4 & 2 & 2 \\ 2 & 2 & 3 & 3 & 1 & 1 \\ 0 & 1 & 2 & 2 & 2 & 1 \end{pmatrix}$$

which entries represent the amount of radiation required. The amount of radiation required is equal to the beam-on time, which will be presented in seconds.

2.2 Leaf Position, Shape Matrix and Set-Up Time

Each row of the intensity matrix represents each channel of the multileaf collimator and as mentioned in section 1.2, a pair of leaves is associated with each channel.

The position a pair of leaves can take for an intensity matrix with n columns, is 0, 1, 2, ..., n . The home positions for the pair of leaves are 0 for the left and n for the right. The left leaf moves towards the right until it gets to the required position and the right leaf moves towards the left for its position. (See Figure 4).

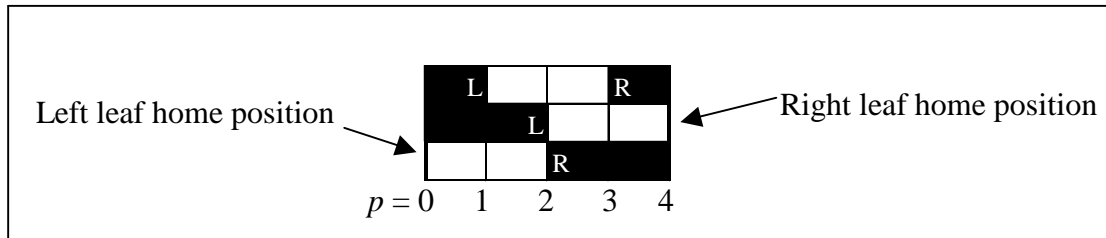


Figure 4: Possible position of the pair of leaves for each channel

Leaf sequencing was formulated as a problem of decomposing the matrix into a series of sub-matrices. A (0,1) matrix, the *shape matrix*, is constructed according to the position of the pair of leaves for each channel of the intensity matrix, a zero entry means the radiation will be blocked by either the left or the right leaf and an entry of one means the cell is open for the radiation. If a channel has its left and right leaf positioned at L and R , respectively, then the corresponding row would have ones in entries $L+1, \dots, R$ and zeros in the rest of the entries. For example, as in Figure 4, the first channel has the left leaf positioned at 1 (L) and the right leaf positioned at 3 (R), the (0, 1) matrix for the first row would have ones in entries 2 ($L+1$) and 3 (R) and zeros in entries 1 and 4. A shape matrix (S) of the configuration in Figure 4 would be:

$$S = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{pmatrix}$$

Associated with each shape matrix is the time the linear accelerator is opened to release uniform radiation, which is the beam-on time. The sum of all shape matrices multiplied by their corresponding beam-on times would equal to the intensity matrix. This can be illustrated by the following example.

Let

$$I = \begin{pmatrix} 0 & 1 & 2 \\ 1 & 3 & 2 \\ 3 & 1 & 1 \end{pmatrix}$$

The following MLC leaf sequences are gathered to shape the intensity profile.

Channel 1	<table border="1"><tr><td>L</td><td></td><td></td><td>R</td></tr></table>	L			R	<table border="1"><tr><td></td><td>L</td><td></td><td></td></tr></table>		L		
L			R							
	L									
Channel 2	<table border="1"><tr><td></td><td></td><td>R</td><td></td></tr></table>			R		<table border="1"><tr><td>L</td><td></td><td></td><td></td></tr></table>	L			
		R								
L										
Channel 3	<table border="1"><tr><td></td><td></td><td></td><td></td></tr></table>					<table border="1"><tr><td></td><td>R</td><td></td><td></td></tr></table>		R		
	R									

The sum of the corresponding shape matrices for the MLC leaf sequences multiplied by their associated beam-on time would be equal to the intensity matrix. This can be written as follows:

$$I = 1S_1 + 2S_2.$$

$$I = 1 \begin{pmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix} + 2 \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

A set up time for each of the MLC leaf sequence is required for the total treatment time. The time for a leaf to move across a cell in either direction is assumed to be a second. The set up time for each channel of the MLC leaf sequence would be the maximum time required to position both the left and the right leaf, for example, the set up time for channel two of the first shape matrix in the example above would be one second. The set up time for a MLC leaf sequence should be the maximum of the set up times of all channels, for example, the set up time for the first MLC leaf sequence of the above example would be one second. All leaves are assumed to be in their home position before moving into position for the first MLC leaf sequence. After the first MLC leaf sequence, leaves will be moved into position from the position of the previous MLC leaf sequence.

3 Previous Work

Numerous algorithms have been developed in order to deal with the multileaf collimator problem. A large number of these algorithms address the dynamic technique (shoot while the leaves are moving). However, the focus here is on those algorithms which output the MLC leaf sequence when dealing with the stop and shoot method, as it was done in [Galvin et al. (1993)], [Webb (1998b)], [Xia & Verhey (1998)], [Siochi (1999)] and [Boland, Hamacher & Lenzen (2000)].

Que W. (1999) compares eight methods of segmentation algorithm to translate beam intensity maps into the least number of MLC leaf sequences. Including the ones by Bortfeld et al., Galvin et al., Xia and Verhey and the Siemens IMFAST algorithm. He found that the algorithm of Xia and Verhey is most frequently the algorithm that needs the least MLC leaf sequences. However, no single algorithm is the most efficient for all clinical cases or intensity maps.

The algorithm proposed by Xia and Verhey (1998) was to minimise the number of segments for an intensity modulated field. In this algorithm the sequence of delivery intensity is proposed to be a series of powers of 2, depending on the maximum intensity level in the matrix. The MLC leaf position sequence is designed directly on the two-dimensional intensity matrix to have the largest possible area, which receives the radiation, in each segment.

Boland, Hamacher and Lenzen (2000) focused on the evaluation of the beam-on time and proposed a model for finding optimal solutions to the leaf positions for MLC as opposed to just heuristic optimisation models such as Xia and Verhey's. They developed a nonlinear mixed integer programming formulation, which can be decomposed to yield a column generation formulation. A network model is developed

for the column generation subproblem. Each path in the network represents a feasible shape matrix and the network model is solved as a shortest path problem.

4 New Model

An integer linear programming model, the Treatment Time Model, is used to model the configuration of the MLC leaf sequence.

4.1 Assumptions

The assumptions for the Treatment Time Model are: the beam head is assumed to be in rectangular shape which is partitioned into equidistant cells (see Section 2.1), the intensity matrix, I , is a given $m \times n$ matrix with integer values in each entry (see Section 2.1), the intensity of the radiation released from the linear accelerator is constant, no leakage of radiation in any manner and the intensity matrix does not contain zero in between any integer numbers.

4.2 Variables

The following variables are being set up for the Treatment Time Model.

Indices

- r = radiation burst: 1, 2, 3, ...
- c = channel: 1, 2, 3, ...
- j = pattern: 1, 2, 3, ...
- t = beam-on time: 1, 2, 3, ...

Parameters

- T = all treatment time in seconds for all radiation burst
- U_{rej} = the set up time for the r th radiation burst of channel c in pattern j
- $L_{cr} = p$ if the left strip of channel c goes to position p at the r th radiation burst
($p = 0, 1, 2, 3, \dots$)
- $R_{cr} = p$ if the right strip of channel c goes to position p at the r th radiation burst
($p = 0, 1, 2, 3, \dots$)

Decision variables

- E_r = the set up time for the r th radiation burst
- $X_{cj} = \begin{cases} 1 & \text{if pattern } j \text{ is used for channel } c \\ 0 & \text{otherwise} \end{cases}$
- $Y_{rt} = \begin{cases} 1 & \text{if run the } r\text{th radiation burst for } t \text{ seconds} \\ 0 & \text{otherwise} \end{cases}$
- $A_{cjrt} = \begin{cases} 1 & \text{if pattern } j \text{ for channel } c \text{ uses } t \text{ seconds for the } r\text{th radiation burst} \\ 0 & \text{otherwise} \end{cases}$

4.3 The Treatment Time Model

The following shows the formulation of the Treatment Time Model.

Objective

$$\text{Minimise } \sum_t T^T * Y_{rt} + \sum_r E_r \quad \forall r \quad (1)$$

Subject to

$$\sum_j X_{cj} = 1 \quad \forall c \quad (2)$$

$$\sum_t Y_{rt} = 1 \quad \forall r \quad (3)$$

$$\sum_j A_{cjr} X_{cj} = Y_{rt} \quad \forall r, t, c \quad (4)$$

$$\sum_j L_{c,r} X_{c,j} - \sum_j R_{c+1,r} X_{c+1,j} \leq 0 \quad \forall r, c \quad (5)$$

$$\sum_j R_{c,r} X_{c,j} - \sum_j L_{c+1,r} X_{c+1,j} \geq 0 \quad \forall r, c \quad (6)$$

$$U_{rej} X_{cj} \leq E_r \quad \forall c, j \quad (7)$$

The objective (1) for the Treatment Time Model is to minimise the total treatment time, which is the sum of the beam-on-time and the set up time for each radiation burst. The constraints for the Treatment Time Model (2) – (7) are described in the following paragraph.

For each channel of I , there are a number of different patterns, which consists configurations satisfying the intensity profile. However, only one pattern for each channel will be selected (2). A range of beam-on time is available for each radiation burst but only one of them can be selected (3). Constraint (4) uses the binary control variables Y_{rt} to ensure that at most only one beam-on time is used for each radiation burst. Overlapping of the opposite neighbouring leaves are not allowed, (5) eliminates the overlapping of the left leaf with the right neighbouring leaf and (6) eliminates the overlapping of the right leaf with the left neighbouring leaf. The set up time for a particular MLC leaf sequence should be greater than the set up time of each channel of the MLC leaf sequence (7). A mathematical model without constraint (7) would be focusing on minimising the total beam-on time.

4.4 Example

An example of a 6×6 intensity matrix is used to illustrate the Treatment Time Model. The example is first being solved focusing on minimising the total beam-on time, then it is solved using the Treatment Time Model being implemented in this project. A comparison is made between the two objectives.

Let

$$I = \begin{pmatrix} 0 & 0 & 4 & 4 & 3 & 0 \\ 0 & 1 & 1 & 6 & 3 & 0 \\ 0 & 0 & 3 & 4 & 1 & 0 \\ 1 & 3 & 4 & 4 & 3 & 0 \\ 0 & 2 & 3 & 6 & 4 & 3 \\ 0 & 1 & 3 & 3 & 4 & 4 \end{pmatrix}$$

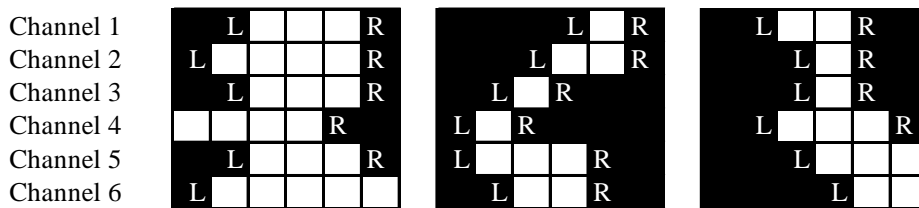
AMPL is being used to implement the model and CPLEX is used to solve the example. The shape matrices and their corresponding beam-on times, which minimise the total beam-on time are shown below. The minimal total beam-on time is six seconds.

$$I = 1S_1 + 2S_2 + 3S_3.$$

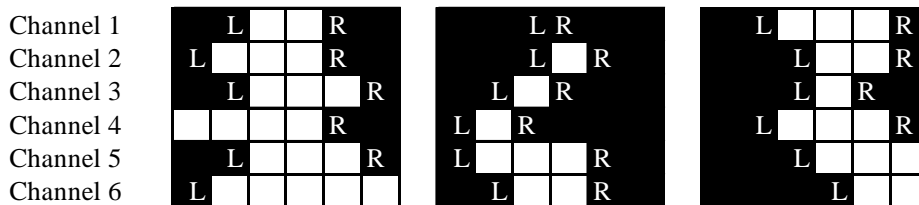
$$I = 1 \begin{pmatrix} 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} + 2 \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{pmatrix} + 3 \begin{pmatrix} 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{pmatrix}$$

The beam-on time associated to each of the shape matrices when solving the example using the Treatment Time Model is the same as above, which the total beam-on time is six seconds. However, the configuration of the MLC leaf sequences for each radiation burst is different. The following shows the change of the configurations of MCL leaf sequence under the two models.

The MLC Leaf Sequence which Minimise the Total Beam-on Time



The MLC Leaf Sequence which Minimise the Total Treatment Time



A linear relaxation of the integer programming is used to solve the problem before getting the optimal integer solution. As a result, the gap in between the optimal solution of the linear relaxation problem and the integer programming problem is very small (0%) when focusing on the total beam-on time, whereas it is relatively large (10%) when the set up time for each MLC sequence is taking into account. Set up times for the first set of MLC sequences have been calculated and compared with the set up times for the second set of MLC sequences and they have turned out to be exactly the same, which proves the existence of the multiple optimal solutions.

5 Conclusion

The above example shows multiple optimal solutions, solutions that have the same objective value but different configurations of the MLC leaf sequence, exist for algorithms either focusing on the total beam-on time or the total treatment time. However, it is less realistic to solve the problem only considering the total beam-on time, as it might be difficult for the cancer patients to be fixed in the same position over

a period of time. The method one implemented in this project is more than less a step closer to reality due to the inclusive of the set up times for each MLC leaf sequence. However, more development on the Treatment Time Model is needed to be able to solve a large-scale clinical problem.

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