Intensity-modulation radiotherapy using independent collimators: An algorithm study

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The purpose of this work is to investigate algorithms for the delivery of intensity-modulated fields using independent collimators (IC). Two heuristic algorithms are proposed to calculate jaw-setting sequences for arbitrary 2D intensity distributions. The first algorithm is based on searching the whole intensity matrix to find the largest nonzero rectangular area as a segment while the second algorithm is to find a nonzero rectangular area as a segment which makes the complexity of the remaining intensity matrix minimum. After a sequence is obtained, the delivery order of all its segments is optimized with the technique of simulated annealing to minimize the total jaw-moving time. To evaluate these two algorithms, randomly generated intensity matrices and three clinical cases of different complexity have been tested, and the results have been compared with one algorithm proposed for MLC technique. It is shown that the efficiency of IC technique becomes increasingly lower than that of MLC technique, and the relative efficiency of two algorithms proposed here is related to machine dose rate and jaw speed. Assuming the prescribed dose is 200 cGy per fraction, machine dose rate is 250 MU/min, and jaw speed is 1.5 cm/s, the treatment can be delivered within about 20 min for all three cases with the first algorithm. The second algorithm requires longer delivery time under such assumptions. The delivery time can be further reduced through increasing machine dose rate and jaw speed, and developing more efficient algorithms. The use of IC for intensity-modulation radiotherapy has some potential advantages over other techniques. © 1999 American Association of Physicists in Medicine. [S0094-2405(99)00712-9]

Key words: independent collimator, algorithm, intensity modulation

INTRODUCTION

Intensity modulation is useful to produce dose distributions that conform three-dimensionally in shape to the target volume while avoiding damage in the neighboring critical organs. A potential benefit of this is that the prescribed dose to the target volume can be escalated while the dose received by the normal tissues can still be kept below tolerance. Earlier attempts to achieve intensity modulation involved the use of physical beam modifiers such as blocks, wedges and compensators.1,2 In recent years, intensity modulation using a multileaf collimator3 or a NOMOS MiMIC system4–5 or a scanning beam6 has been investigated, and is now commercially available. Among these techniques, the most popular one is the use of MLC, which can be carried out either in static segmental mode7–9 or in dynamic mode.10–14 Independent collimator (IC), a standard accessory of modern linear accelerator, has been used to deliver a linear intensity distribution in one direction (i.e., dynamic wedge or virtual wedge). It can also be used to generate arbitrary intensity profiles.11,12 However, it is usually believed that the use of IC for 2D intensity modulation is clinically impractical, since it takes too long to deliver a treatment. For example, when using dual dynamic asymmetric jaw pairs for intensity modulation, Brahme estimated the treatment time would be 20 times longer than the standard treatment time of about 1 min for uniform dose delivery.15 As there has been no detailed research on this subject, we propose two heuristic algorithms here to calculate IC jaw-setting sequences for arbitrary 2D intensity distributions and to use the technique of simulated annealing to optimize the delivery order of all segments in a sequence. In order to evaluate these two algorithms, both randomly generated intensity matrices and clinical cases were tested, and the results were compared with those of one algorithm proposed by Xia and Verhey for MLC technique.7

METHODS

Calculation of IC jaw-setting sequence

The desired intensity distribution of a beam can be described by a matrix ID0(m,n), where m is the matrix size in the collimator’s X direction and n the matrix size in the Y direction. The intensity at any element can be represented by an integer between zero and the maximum intensity level MaxI. One simple example of intensity matrices is shown in Fig. 1, where m=n=4 and MaxI=5. For calculating IC jaw-setting sequences, we chose a coordinate system whose origin was set at the lower-left corner of the matrix and the axes were parallel to the moving direction of the collimator jaws. The calculated IC jaw-setting sequence in this coordinate system would be transformed into the collimator system when the final delivery file is generated and sent to the treatment machine.

A specific intensity matrix can be delivered by quite a few different IC jaw-setting sequences. The best algorithm should determine the jaw-setting sequence with minimum
delivery time. The simplest, but also the least efficient method is to irradiate matrix elements one by one. Alternatively, a method, which is somewhat more efficient, is to use the IC as a pair of MLC leaves, and to irradiate matrix rows one by one. We developed two heuristic algorithms with the aim of improving the delivery efficiency.

The first algorithm (designated IC-A1) is based on searching the whole matrix to find the largest nonzero rectangular area as a segment. The procedure is as follows:

(1) Initially, search the entire matrix ID_0(m,n) to find the first segment $S_1$ that covers the largest area, and determine the IC jaw-settings $(X_{11}, X_{21}, Y_{11}, Y_{21})$ and the intensity IS_1 of segment $S_1$. For the case shown in Fig. 1, jaw-settings of $S_1$ are $X_{11}=0$, $X_{21}=4$, $Y_{11}=2$, $Y_{21}=4$, and IS_1=1.

(2) Subtract IS_1 from the intensity of all matrix elements which are included in the segment $S_1$, and obtain a new intensity matrix ID_1(m,n).

(3) Repeat steps (1) and (2), find the largest segment $S_i$ for the intensity matrix ID_{i-1}(m,n) until the remaining intensity matrix ID(m,n) is zero.

The second algorithm (named IC-A2) is based on searching the whole matrix to find a nonzero rectangular area as a segment, such that the “complexity” of the remaining intensity matrix is minimum. The “complexity” of an intensity matrix is measured by the number of “blocks” in it, where a “block” is defined as the largest rectangular area formed by elements of nonzero equal intensity level. Each element belongs exclusively to one block. For the case shown in Fig. 1, there are one block of intensity level 1 and one block of intensity level 4 that contain two elements while all other blocks contain only a single element. There are 13 “blocks” in the intensity matrix. The procedure of Method 2 is described as follows:

(1) Find one element that has the highest intensity from the initial intensity matrix ID_0(m,n).

(2) Around this element, determine the IC jaw-settings $(X_{11}, X_{21}, Y_{11}, Y_{21})$ and the intensity IS_1 of the first segment $S_1$ such that the complexity of the remaining intensity matrix is minimum. For the case shown in Fig. 1, jaw-settings of $S_1$ are $X_{11}=2$, $X_{21}=4$, $Y_{11}=0$, $Y_{21}=4$, and IS_1=1. The complexity of the remaining intensity matrix is 10.

(3) Subtract IS_1 from the intensity of all matrix elements included in the segment $S_1$, and obtain a new intensity matrix ID_1(m,n).

(4) Repeat steps (1) through (3), find the segment $S_i$ for the intensity matrix ID_{i-1}(m,n) until the remaining intensity matrix ID(m,n) is zero.

Optimization of the delivery order of all segments

After all segments in a sequence are determined with algorithm IC-A1 or algorithm IC-A2, their delivery order needs to be optimized in order to minimize the total jaw-moving time. When jaw positions vary from one segment to the next, four jaws begin to move simultaneously, but usually they do not arrive at the same time. Since it is the longest moving time that affects the delivery time, the total jaw-moving time of the sequence $T_M$ is defined as the sum of the longest moving time among the four jaws when they move from one segment to the next through the sequence.

$$T_M = \sum_{i=2}^{N} \max \left( \frac{|X_{1,i-1}-X_{1,i}|}{V_x}, \frac{|X_{2,i}-X_{2,i-1}|}{V_x}, \frac{|Y_{1,i}-Y_{1,i-1}|}{V_y}, \frac{|Y_{2,i}-Y_{2,i-1}|}{V_y} \right)$$

where $N$ is the number of segments; max is the function for the maximum value among several variables; $i-1$ and $i$ are the indices of two consecutive segments; $X_{1,i}$ and $X_{2,i}$ are the $X$ jaw settings of $i$th segment; $Y_{1,i}$ and $Y_{2,i}$ are the $Y$ jaw settings of $i$th segment; $V_x$ and $V_y$ are the jaw speeds in $X$ and $Y$ directions, respectively.

The problem here is to find the delivery order of all segments that yields the minimum value of $T_M$. This problem is similar to that of the traveling salesman problem that can be solved with simulated annealing technique. For the specific problem here, the simulated annealing procedure is as follows:

(1) Choose a section of segments from the sequence. The start and end segments of the section are determined randomly.

(2) Rearrange the section. There are two types of rearrangements: (a) the section is replaced with itself with the segments running in the reverse order; or (b) the section is removed and then inserted in another randomly chosen part of the sequence. The probability of adopting each type of rearrangement is equal.

(3) Calculate the change $\Delta T_M$ in the jaw moving time. If $\Delta T_M<0$, i.e., decreased jaw moving time, then keep the rearrangement. If $\Delta T_M>0$, i.e., increased jaw moving
time, then keep or reject the rearrangement based on a probability $p = \exp(-\Delta T_M/T)$, where “$T$” is the “temperature,” a parameter that controls the likelihood of accepting an “adverse” rearrangement that would result in an increased $T_M$. In practice, a random number $r$ between 0 and 1 is chosen and compared with $p$. If $r < p$, keep the rearrangement, otherwise reject it. Initially the temperature “$T$” is set to a relatively high value (say, 1.0 here) to avoid the solution being trapped in a local minimum. As the procedure proceeds, “$T$” is then gradually reduced (see step 5).

(4) Repeat steps (1) to (3) for 100N rearrangements or 10N successfully rearrangements, whichever comes first. Steps (1) through (4) complete one iteration.

(5) Reduce the temperature by some fraction, say, 10%. Repeat steps 1 to 4 for a number of iterations defined by the user (typically 100 iterations).

**Evaluation of algorithms**

The number of segments in a sequence and the modulation-scaling factor (MDF) are indexes for estimating the efficiency of an algorithm for IC or MLC segmental intensity modulation. Similar to the definition of MLC’s MDF, IC’s MDF can be defined as

$$\text{MDF} = \Phi_{ic}/\Phi_{phys},$$

where $\Phi_{ic}$ is the total intensity on the sequence of IC segments, $\Phi_{phys}$ is the intensity incident on the physical compensator.

Since $\Phi_{ic} = c \sum_{i=1}^{N} IS_i$, and $\Phi_{phys} = c \cdot \text{MaxI}$, where $c$ is the scaling factor relating the relative intensity to the absolute intensity, Eq. (2) can be simplified as

$$\text{MDF} = \frac{\sum_{i=1}^{N} IS_i}{\text{MaxI}}.$$  

If one algorithm requires a smaller number of segments and has a lower MDF than another, it is certain that the efficiency of the former algorithm is higher than the latter one. Nevertheless, when one algorithm requires a smaller number of segments but has a higher MDF than another, or vice versa, we could not be certain which one is more efficient. A third index, namely delivery time, is needed to deal with such situation. The delivery time reflects the composite effect of the previous two indexes. If one algorithm requires a smaller delivery time than another, it is certain that the efficiency of the former algorithm is higher than the latter. Otherwise, the latter would have a higher efficiency.

For conventional radiotherapy, the delivery time, $T_D$, is just the beam-on time. For IMRT in static segmental mode, no matter with MLC or IC, beam is turned off when leaves or jaws move. Therefore, the delivery time consists of the beam-on time, $T_B$, and the leaf or jaw-moving time, $T_M$, that is

$$T_D = T_B + T_M.$$  

where $T_M$ is the jaw-moving time given by Eq. (1), and $T_B$ is given by

$$T_B = \left(\sum_{i=1}^{N} IS_i \cdot \text{MUPI}\right)/\text{MUR},$$

where $IS_i$ is the intensity of the $i$th segment, MUPI is the machine monitor number per intensity level, and MUR is the machine dose rate. If a machine has several levels of dose rate, we will choose the maximum level on view of reducing beam-on time.

IC technique introduced here is similar to segmental MLC technique. This makes comparisons with MLC technique a convincing way to estimate the efficiency of IC technique. As mentioned above, MLC technique has been investigated extensively. Bortfeld et al. proposed to set the delivery intensity sequence to intensity unit 1. Galvin et al. proposed to set the delivery intensity sequence to intensity power of 2, and compared their algorithm with that proposed by Bortfeld et al. and that by Galvin et al. The results showed that their algorithm resulted in the smallest number of segments with moderately increased monitor units. Therefore the algorithm for MLC technique proposed by Xia and Verhey is used here as a benchmark to estimate the efficiency of two IC algorithms for IC technique proposed here. For convenience, their algorithm is designated as MLC-A here. For some accelerators such as Siemens KD2, MLC interleaf motion is prohibited, which results in an increase of 25% in the number of segments. However, there is no such constraint with IC. In order to achieve strict comparison, the results here with MLC algorithm are without interleaf constraint. Either with IC jaws or MLC leaves, there is a problem of over-travel limit. Such limits are the definition ranges of parameters from mathematical view. If it is violated, what the algorithm can do is to inform its occurrence. The real solution to avoid its occurrence is to increase the over-travel distance mechanically. Therefore the over-travel limit of IC jaws and MLC leaves is neglected.

**RESULTS**

**A simple example**

Two delivery sequences were calculated for the simple intensity matrix in Fig. 1 with two IC algorithms proposed here. The delivery order of all segments in each sequence was optimized with the technique of simulated annealing. For the delivery sequence with algorithm IC-A1, the total number of segments is 12, and the total intensity is 15. Since the maximum intensity level in this intensity matrix is 5, this delivery sequence’s MDF is 3.0. For that with algorithm IC-A2, the total number of segments is 10, the total intensity is 17, and the MDF is 3.4. Table I lists the optimized delivery order, the initial delivery order, the jaw settings, and the intensity of every segment in each sequence.

As a comparison, a delivery sequence was also calculated with algorithm MLC-A, and optimized with the technique of...
simulated annealing. For this delivery sequence, the total number of segments is 6, the total intensity is 9, and the MDF is 1.8. The corresponding MLC shapes are shown in Fig. 2 according to their optimized delivery order.

**Comparison of random examples**

1000 examples of intensity maps were generated randomly for calculating IC and MLC sequences for a specific combination of matrix size and nonzero intensity level. The matrix size was set to be 5×5, 10×10, and 15×15, respectively. For each matrix size, the nonzero intensity levels varied from 1 to 16 with a step of 1.

It is shown in Fig. 3 and Table II that the average number of segments increases with the number of intensity levels for the same matrix size for all three algorithms. Within the same intensity level, IC-A1 requires the largest number of segments, algorithm IC-A2 requires a number of segments somewhat smaller, and algorithm MLC-A requires the smallest number of segments. The difference in the number of segments between IC-A1 and IC-A2 is much smaller than that between IC-A1 (or IC-A2) and MLC-A. The average number of segments of 15×15 matrices presented here for algorithm MLC-A is close to that given in Ref. 7. For example, when the number of intensity levels is 10, the average number of segments is 20.2±1.2 here and 20.5±1.2 in Ref. 7.

As shown in Fig. 4, when keeping the number of intensity levels constant, the average number of segments increases linearly for all three algorithms as the matrix size (i.e., the number of elements in a matrix) increases. Because the increasing speed for algorithms IC-A1 and IC-A2 is higher than that for algorithm MLC-A, the difference in the average number of segments between IC-A1 (or IC-A2) and MLC-A increases with the matrix size. Within 10 nonzero intensity levels, when the matrix size is 5×5, 10×10, and 15×15, the ratio of the number of segments for IC-A1 to that for MLC-A is 2.4, 4.9, and 7.6, respectively. The values of the corresponding ratio of IC-A2 to MLC-A are 2.1, 4.2, and 6.5, respectively, which are smaller.

Figure 5 and Table III show the average MDF of 1000 examples of 5×5, 10×10, and 15×15 matrices. For the same matrix size, the average MDF decreases increasingly slowly with the increase of the number of intensity levels for algorithms IC-A1 and IC-A2, and saturates gradually. The curve of the average MDF for algorithm MLC-A has minima at intensity levels 2, 5, 7, 11, and 15. No matter how high is the number of intensity levels, MLC algorithm has the lowest MDF. When the number of intensity levels is 1, algorithm IC-A1 has a MDF slightly greater than algorithm IC-A2 does. When the number of intensity levels is 2, algorithms IC-A1 and IC-A2 have almost the same MDF. When the number of intensity levels is larger than 2, algorithms IC-A1 always has a MDF less than algorithm IC-A2 does.

<table>
<thead>
<tr>
<th>Algorithm IC-A1</th>
<th>Algorithm IC-A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>$X_1$</td>
</tr>
<tr>
<td>1(12)</td>
<td>3</td>
</tr>
<tr>
<td>2(7)</td>
<td>3</td>
</tr>
<tr>
<td>3(6)</td>
<td>3</td>
</tr>
<tr>
<td>4(4)</td>
<td>2</td>
</tr>
<tr>
<td>5(3)</td>
<td>0</td>
</tr>
<tr>
<td>6(1)</td>
<td>0</td>
</tr>
<tr>
<td>7(5)</td>
<td>0</td>
</tr>
<tr>
<td>8(11)</td>
<td>1</td>
</tr>
<tr>
<td>9(9)</td>
<td>1</td>
</tr>
<tr>
<td>10(2)</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 2. MLC shapes of the delivery sequence for the intensity matrix in Fig. 1 with two algorithms proposed here. IC-A1 is the first algorithm, and IC-A2 is the second one. No is the delivery order of one segment. The value of No inside parentheses is the initial delivery order of one segment, and the corresponding value of No outside parentheses is the optimized delivery order of this segment. $X_1, X_2, Y_1, Y_2$ are the jaw settings, and IS is the required intensity of one segment.
The difference in MDF between IC-A1 and IC-A2 is much smaller than that between IC-A1 or IC-A2! and MLC-A. When converting MDF into the total intensity on a sequence using Eq. 3, we can also see the close consistency between the results presented here and that given in Ref. 7.

As shown in Fig. 6, when keeping the number of intensity levels constant, the average MDF increases linearly for all three algorithms as the matrix size increases. Because the increase in speed of the average MDF for algorithms IC-A1 and IC-A2 is higher than that for algorithm MLC-A, the differences in the average MDF between IC-A1 (or IC-A2) and MLC-A also increase with the matrix size. When the matrix size is 5×5, 10×10, and 15×15, the ratio of the average MDF for IC-A1 to that for MLC-A is 2.4, 4.6, and 6.9, respectively. The values of the corresponding ratio of IC-A2 to MLC-A are 2.6, 4.9, and 7.4, which are greater.

Since the ratio of the average number of segments and the ratio of the average MDF between algorithm IC-A1 (or IC-A2) and algorithm MLC-A increases with matrix size, the efficiency of IC technique becomes increasingly lower than that of MLC technique as the field size increases. The difference in efficiency between two IC algorithms is much smaller than that between them and algorithm MLC-A. If beam-on time contributes more to the delivery time than jaw-moving time, algorithm IC-A1 will have a higher efficiency. Otherwise, algorithm IC-A2 will have a higher efficiency.

### Table II. Variation of the average number of segments with matrix size and intensity levels by using two IC algorithms and one MLC algorithm. IC-A1 and IC-A2 are the first and the second algorithm proposed here, MLC-A is proposed by Xia et al. (Ref. 7).

<table>
<thead>
<tr>
<th>Matrix size</th>
<th>Levels</th>
<th>IC-A1</th>
<th>IC-A2</th>
<th>MLC-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>5×5</td>
<td>1</td>
<td>6.4±1.2</td>
<td>6.2±1.1</td>
<td>2.1±0.4</td>
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<tr>
<td></td>
<td>5</td>
<td>14.8±1.7</td>
<td>13.2±1.4</td>
<td>5.8±0.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>18.3±1.7</td>
<td>16.0±1.4</td>
<td>7.6±0.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>20.0±1.6</td>
<td>17.5±1.3</td>
<td>8.3±0.8</td>
</tr>
<tr>
<td>10×10</td>
<td>1</td>
<td>23.7±2.2</td>
<td>23.1±2.2</td>
<td>3.9±0.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>55.5±3.1</td>
<td>49.1±2.6</td>
<td>10.7±1.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>69.1±3.2</td>
<td>59.5±2.5</td>
<td>14.1±1.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>76.0±3.1</td>
<td>64.7±2.5</td>
<td>15.3±1.0</td>
</tr>
<tr>
<td>15×15</td>
<td>1</td>
<td>52.2±3.5</td>
<td>50.7±3.4</td>
<td>5.6±0.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>122.0±4.6</td>
<td>108.0±3.9</td>
<td>15.3±1.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>152.7±4.6</td>
<td>130.6±3.8</td>
<td>20.2±1.2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>168.1±4.7</td>
<td>142.6±3.9</td>
<td>22.0±1.2</td>
</tr>
</tbody>
</table>

**Fig. 3.** Variation of the average number of segments as a function of intensity levels for three algorithms. (a) 5×5 matrices, (b) 10×10 matrices, and (c) 15×15 matrices.

**Fig. 4.** Variation of the average number of segments as a function of matrix size for three algorithms when the number of intensity levels is fixed to be 10. The matrix size is given by the number of elements in an intensity matrix.
Comparison of clinical examples

Clinical intensity maps are less complex than random maps since neighboring elements in the matrix are, to a certain extent, correlated with one another. When the complexity of an intensity map decreases, the number of segments and the MDF will decrease accordingly. Three clinical cases of different complexity were chosen, one breast, one prostate, and one nasopharynx. The breast case has two fields, and can be taken as the representative of the simplest. The prostate case has five fields, and can be taken as the representative of medium complexity. The nasopharynx case has seven fields, and can be taken as the representative of the most complex. Absolute intensity maps in unit of MU were obtained for target dose 100 cGy per fraction by using the treatment planning system developed by Memorial Sloan-Kettering Cancer Center. The grid size of absolute intensity maps was 0.2 cm in the collimator X direction and 1.0 cm in the Y direction. These absolute intensity maps were converted into relative ones with 10 nonzero intensity levels for calculating the delivery sequence. The element size of relative intensity maps was set to be 1.0 cm in both X and Y direction. Five grid points in an absolute intensity map in the X direction were combined into one element in the corresponding relative intensity matrix. The relative intensity level at this element is calculated from the average absolute intensity of these five grid points. The delivery sequence was calculated for three algorithms. Using a number of simple
assumptions, then, the delivery order of all segments was optimized, and the delivery time was calculated. The assumptions used in this calculation were a prescribed dose of 200 cGy, a dose rate of 250 MU/min, a jaw and leaf speed of 1.5 cm/s. The process of optimizing the delivery order, and calculating the delivery time for algorithm MLC-A was similar to that for two IC algorithms. The CPU time for calculating a sequence increased with the matrix size and the number of intensity levels. To determine a jaw-setting sequence for one clinical field took 1 to 4 s on a SGI Indy workstation for algorithm IC-A1, and 2 to 110 s for algorithm IC-A2. The CPU time for optimizing the delivery order depended on the number of segments that were also related to the matrix size and the number of intensity levels. For all three cases here, it was less than 3 s.

Table IV lists three cases’ results. The average matrix size per field of breast, prostate, and nasopharynx case is 18×18, 10×10, and 15×15, respectively. Comparing with randomly generated intensity matrices, the average number of segments and the average MDF per field of every case decrease significantly. For all three algorithms, the average number of segments per field is about one-half of that shown in Fig. 3 and Table II for randomly generated intensity matrices of the same size. For example, the average number of segments per field in prostate case is 32.8, 29.4, and 8.0 for algorithm IC-A1, IC-A2, and MLC-A, respectively, while the corresponding average number of segments for 10×10 random matrices is 69.14, 59.53, and 14.06, respectively. The average MDF is about one-fourth of that shown in Fig. 5 and Table III for randomly generated intensity matrices of the same size when IC-A1 or IC-A2 is used, and one-half of that when MLC-A is used. For example, the average MDF per field in prostate case is 4.08, 5.10, and 1.67 for algorithm IC-A1, IC-A2, and MLC-A, respectively, while the corresponding average MDF for 10×10 random matrices is 16.81, 17.98, and 3.65, respectively. The greater decrease in MDF for two IC algorithms than for the MLC algorithm is beneficial for reducing the difference in beam-on time between IC technique and MLC technique, and then the difference in delivery time.

For all three cases, IC-A2 requires the longest beam-on time and a shorter jaw-moving time, algorithm IC-A1 requires a shorter beam-on time and the longest jaw-moving time, and algorithm MLC-A requires the shortest beam-on time and the shortest leaf-moving time. Depending on the field matrix size, the beam-on time for IC-A2 is about 3 to 9 times as long as that for MLC-A, and the beam-on time for IC-A1 is about 2.5 to 7 times as long as that for MLC-A. The total initial jaw-moving time for IC-A1 is about 2 to 10 times as long as that for MLC-A, and the total initial jaw-moving time for IC-A2 is about 2 to 7.5 times as long. Through optimizing the delivery order of all segments in the sequence, the total jaw-moving time decreases by about 70% for two IC algorithms, and the total leaf-moving time decreases only by about 10% for the MLC algorithm. So the difference between the total optimized jaw-moving time for two IC algorithms and that for MLC algorithm decreases to 0.1~3 min. The reason why the decrease in MLC leaf-moving time is much smaller than IC jaw-moving time is that there are much more than 4 leaves to move while there are only 4 jaws to move when another segment needs to be formed. This different decrease in total jaw- and leaf-moving time is also beneficial for reducing the difference in delivery time between IC and MLC techniques. For all three cases, algorithm IC-A2 requires the longest delivery time, algorithm IC-A1 requires a shorter delivery time than IC-A1, and algorithm MLC-A requires the shortest delivery time among three algorithms. Depending on the field matrix size, the delivery time for algorithm IC-A1 is about 2 to 5 times as long as that for MLC-A, and the delivery time for algorithm IC-A2 is about 2 to 5.5 times as long. The treatment of breast, prostate, and nasopharynx case can be delivered in 14.85, 8.77, and 21.23 min, respectively, with algorithm IC-A1, in 17.30, 10.27, and 22.85 min with algorithm IC-A2, and in 3.08, 5.06, and 9.13 min with algorithm MLC-A. It is shown that the efficiency of IC technique is about 20% to 50% of the efficiency of MLC technique. This result is much better than what people usually think. The relative efficiency of two IC algorithms is related to machine dose rate and jaw speed. Under the assumptions used here, algorithm IC-A1 is more efficient than algorithm IC-A2. Nevertheless, for a ma-
machine with a lower dose rate and higher jaw speed, algorithm IC-A2 is perhaps more efficient.

**DISCUSSION**

It has been shown that quite a few factors affect the delivery time. These include machine dose rate, jaw speed, the number of fields, prescribed dose, jaw-setting sequencing algorithm, and intensity matrix size as well as the number of intensity levels. The beam-on time is proportional to the prescribed dose, inversely proportional to machine dose rate while the jaw-moving time is positively correlated to the number of fields and the number of intensity levels, and inversely proportional to jaw speed. The ways to reduce the delivery time for IC based IMRT are as follows:

1. Increase machine dose rate. It is found in Table IV that the beam-on time contributes more to the delivery time than the jaw-moving time does for all three cases when two IC algorithms are used. So increase in machine dose rate is an efficient way to reduce the delivery time. If machine dose rate can be increased from 250 MU/min to 500 MU/min which is now available on some new types of machines, the delivery time of breast, prostate and nasopharynx case will decrease from 14.85, 8.77, and 21.23 to 8.82, 5.72, and 15.28 min, respectively, when algorithm IC-A1 is used.

2. Control reasonably the number of fields and the number of intensity levels without deteriorating the treatment outcome. In this way, the total number of segments can be reduced, and so does the jaw-moving time. The question of how many fields are necessary to obtain an optimum plan has been investigated extensively. There is some evidence that three to nine beams is generally sufficient. Verhey et al. reported that four carefully forward planned coplanar fields of three intensity levels produced excellent dose volume histograms that were equal to or better than those generated by a plan using 10 intensity levels and five equally spaced fields.

3. Increase jaw speed if possible so as to decrease the jaw-moving time. This is more useful to those complex cases as the nasopharynx case than to those simple cases as the breast. If jaw speed can be increased from 1.5 cm/s to 3.0 cm/s, the delivery time of the nasopharynx case will decrease from 21.23 min to 16.56 min for algorithm IC-A1 while the delivery time of the breast will only decrease from 14.85 min to 13.23 min for algorithm IC-A1.

4. Develop new algorithms. Although two algorithms presented here results in a delivery time clinically acceptable, neither of them is the real solution to the problem of minimizing the delivery time given by Eq. (4). Therefore, it is possible and meaningful to develop algorithms that are more efficient.

Besides the efficiency concern for using IC for IMRT, the over-travel limit of jaws is also a major concern. The over-travel distance of X jaws is shorter than that of Y jaws on most types of linear accelerators commercially available such as Varian 600C and Siemens KD2. Varian 600C’s X jaws can travel up to the central axis and its Y jaws can over-travel up to 10 cm. The over-travel distance of X jaws and Y jaws is 2 and 10 cm, respectively, on Siemens KD2. 10 cm over-travel distance is sufficient for IC based IMRT. However, 2 cm or even shorter over-travel distance is too short to be used. The ideal solution to this problem is to have the accelerator vendor to replace the X jaws with new ones that can travel up to 10 cm or even more beyond the central axis. A less desirable solution is to have the user attach a pair of computer-controlled blocks below the collimator. As mentioned above, this problem has no chance to be overcome by a jaw-setting sequencing algorithm.

The use of IC has some advantages over other available techniques:

1. It is much less laborious than the use of physical beam modifiers.

2. The matrix element size can be adjusted continuously in the X and Y directions whereas the MLC leaf width is usually fixed to about 1 cm; and the element size of NOMOS MiMIC system is fixed to either 1.0×0.84 or 1.0×1.68 cm². In some cases, smaller element size is beneficial for shaping irregular target volumes.

3. It has dosimetric advantages over MLC technique. It can avoid ‘‘tongue and groove’’ problem and keep a narrow penumbra. It also has no interleaf constraint.

4. It is much easier to control and maintain an IC than a MLC, a mini-multileaf collimator or a scanning beam.

**CONCLUSION**

Two algorithms are presented for calculating jaw-setting sequences for IC based intensity modulation radiotherapy, and the technique of simulated annealing is presented to optimize the deliver order of all segments in a sequence. Their efficiency has been tested with both randomly generated intensity matrices and three clinical cases through comparing with a MLC algorithm. The treatment of a clinical case can be delivered within about 20 min when the prescribed dose is 200 cGy, machine dose rate is 250 MU/min, and jaw speed is 1.5 cm/min. The delivery time can be further reduced through increasing machine dose rate, increasing jaw speed, developing more efficient algorithms, and so on. The use of IC has some potential advantages over other techniques.

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