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The generation of intensity-modulated fields for conformal radiotherapy by dynamic collimation

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Abstract. An algorithm has been developed to calculate the collimator jaw motions required to generate intensity-modulated fields for use in conformal radiotherapy. The dynamic technique allows arbitrary intensity profiles to be generated using a single unidirectional sweep of the collimators. The collimator jaws have independent motion, so that an aperture of variable width is scanned across the field. The algorithm has the form of a constrained optimization problem and jaw motions are optimized such that the treatment time for the field at a given dose rate is minimized. The application and results of this technique are presented, and it is shown that this approach provides an efficient practical implementation of conformal radiotherapy plans based on the use of intensity-modulated fields. The technique can be extended to 3D treatment plans and fields through the use of computer-controlled multileaf collimators.

1. Introduction

In recent years a novel approach to external beam radiotherapy treatment planning has been introduced and developed (Brahme 1987, 1988, Censor *et al* 1988, Powlis *et al* 1989, Webb 1989, 1991, Bortfeld *et al* 1990, Holmes *et al* 1991) based on the use of fields in which the intensity is allowed to vary across the beam. Using such intensity-modulated fields it is possible to correct not only for contour irregularities and tissue inhomogeneities, but more significantly one can also *shape* the spatial dose distribution within the patient such that the high dose region conforms more closely to the prescribed target volume. Indeed, this technique is sufficiently powerful to allow the generation of concave dose distributions and to provide sparing of organs at risk within complex treatment geometries.

A common feature of the different implementations of this new approach is the determination of the intensity profiles required to produce a specified dose distribution within the patient, with the solution to the planning problem being a set of irregular intensity profiles, one for each field in each plane of the plan, which must be generated at treatment. These profiles may be generated in several ways. The most obvious approach is to differentially attenuate the fluence across the beam using an individually shaped attenuator for each field, i.e., fabricating a compensator for each field of the plan. This, however, has drawbacks. Individual compensators have to be made for each field of the plan and their use adds to overall treatment times due to the need to

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change them between fields. This becomes particularly significant for plans requiring concave treatment volumes, for which Bortfeld *et al* (1990) have shown that seven or nine fields are generally required.

An alternative approach that is flexible enough to be applied equally to all fields and which does not interrupt treatment between fields would clearly be attractive. One such option is *dynamic collimation*—motion of the collimator jaws during irradiation. This clearly provides the facility to modulate the intensity across the field within the plane through which the jaws move, the degree to which this is possible depending on the allowed motion. The extension of this to three-dimensional treatment, where it is necessary to vary the intensity throughout the entire field, may be achieved using a multileaf collimator, as discussed in section 4. Dynamic therapy of this form may be implemented on linear accelerators in which the collimator positions are under computer control and may be varied during irradiation. The collimator jaws must be able to cross the central axis. Treatment could then be carried out completely under computer control without the need to pause between fields to change the set-up. Each field would be generated by dynamic collimation, with the set-up of the next field also achieved automatically by computer control.

If motion is restricted to just one jaw then the profile generated by a single irradiation will be monotonically increasing (as with the dynamic wedge (Kijewski *et al* 1978)), while if the jaws 'close in' on a single point (or open out from that point) then the field profiles will have a single maximum and decrease as we move out from it. Such restrictions obviously severely limit the type of intensity-modulated fields that may be generated by a single irradiation, although the use of successive irradiations of the field would allow more complex profiles to be produced.

The algorithm presented in this paper has been developed to overcome these problems. The technique is based on moving both jaws across the field in the same direction with independent motion, in effect sweeping an aperture of variable width across the field. This is shown to allow the generation of arbitrary intensity profiles using only a single unidirectional sweep of the collimator jaws across the field. Collimator motion is optimized such that the most efficient dynamic irradiation is achieved.

It should be noted that this paper deals only with the question of how to implement conformal radiotherapy treatment plans that employ intensity-modulated fields. It is assumed that the required intensity profiles have been calculated previously by a treatment planning program and that one now wants to determine how to generate these profiles. In the analysis of the problem presented below, collimator scatter, leakage and penumbra have been omitted. These simplifications have enabled the present preliminary investigations into the feasibility of this dynamic approach to be undertaken and a clear statement of the principles and operation of the algorithm to be given. These factors will, of course, have to be included in any practical implementation of the algorithm. Photon scatter and charged particle transport in the phantom do not, however, need to be included as their effects must be incorporated at the treatment planning stage when determining the field intensity profiles required.

2. The determination of collimator motion required to generate irregular field intensity profiles—a numerical algorithm

The problem of generating a required intensity modulation within a single plane by dynamic collimation is first solved. The extension of this work to fields in which the intensity modulation varies from plane to plane (i.e., from slice to slice within the 3D plan) is dealt with in section 4.

A schematic diagram of the geometry is given in figure 1. The coordinate system has its origin at the source and z-axis down the central ray, with the x-axis measuring lateral displacement from the central ray. The collimator jaws in the x,z-plane are labelled A and B. It is assumed for convenience that the jaws move in the positive x-direction. The intensity modulation across the beam, which will have been calculated by a conformal therapy planning program of the type discussed in the introduction, is defined by the in-air profile in the plane $z = z_{ref}$, conventionally the plane through the isocentre. This in-air profile defines an effective variation of the number of monitor units per ray line across the field, and is referred to as the field intensity profile. This is the number of monitor units each part of the field requires in order to produce this in-air profile.

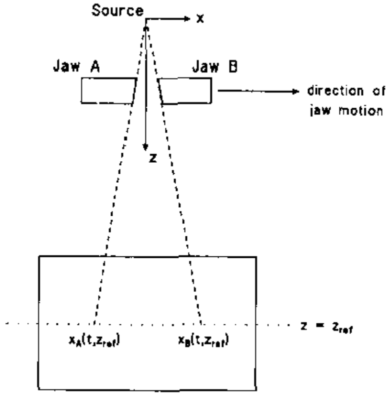

Figure 1. Schematic diagram illustrating the geometry and coordinate system used. Motion of the collimator jaws across the field can be used to vary the fluence in the plane in which the jaws move. Dynamic collimation of this form can be used to generate intensity-modulated fields for use in conformal radiotherapy.

2.1. *Definitions and notation*

$T(x, z_{ref})$ is the field intensity profile to be generated—this is the variation across the field of the number of monitor units to be delivered (defined at depth $z = z_{ref}$); $x_A(t, z_{ref})$ is the position of jaw A after t monitor units (MU) on plane $z = z_{ref}$; $x_B(t, z_{ref})$ is the position of jaw B after t MU on plane $z = z_{ref}$; $t_A(x, z_{ref})$ is the cumulative number of MU at which jaw A is at position (x, z_{ref}); and $t_B(x, z_{ref})$ is the cumulative number of MU at which jaw B is at position (x, z_{ref}). The aim of the algorithm is to determine the collimator jaw motions, $x_A(t, z_{ref})$ and $x_B(t, z_{ref})$, that will produce the field intensity profile, $T(x, z_{ref})$, in the most efficient way possible.

2.2. *Numerical algorithm*

The dynamic technique presented in this paper allows the generation of an arbitrary intensity profile across a beam by moving both jaws across the field with independent motion, so that the aperture being scanned is of varying width. Only a single unidirectional sweep of the jaws across the field is required. The technique is quite general and allows the generation of irregular intensity profiles of arbitrary shape, such as those having several maxima and minima. The algorithm derived below determines the jaw motions from the given field intensity profile. This is done in two stages: $t_A(x, z_{ref})$ and $t_B(x, z_{ref})$ are first determined and from these $x_A(t, z_{ref})$ and $x_B(t, z_{ref})$ are easily calculated.

From the definitions of $t_A(x, z_{ref})$ and $t_B(x, z_{ref})$ above, we have

$$t_A(x, z_{ref}) - t_B(x, z_{ref}) = T(x, z_{ref}). \tag{1a}$$

In this problem, however, the intensity profile is known only at a discrete set of points, $\{(x_i, z_{ref})\}$. These would be determined by the relative weighting of ray-lines in the field (i.e. the intensity modulation across the beam) calculated by a conformal radiotherapy treatment planning program. Equation (1*a*) must therefore be replaced by the *set* of equations

$$t_A(x_i) - t_B(x_i) = T(x_i) \qquad i = 1, N \tag{1b}$$

where N is the number of points (x_i, z_{ref}) defining the profile, and the z_{ref} term has been dropped as the field intensity, jaw positions and cumulative monitor units are all functions of x within the reference plane. The problem therefore reduces to finding the sets of values, $\{t_A(x_i)\}$ and $\{t_B(x_i)\}$, which satisfy equation (1*b*) above, subject to constraints derived below.

For the model (and consequently the solution) to be physically realistic it is necessary to impose constraints on the allowed jaw motions. These are set by defining an upper limit, ν_{max}, to the jaw velocity. An absolute upper limit to ν_{max} will be set by the maximum speed at which the jaws of a computer-controlled linear accelerator can move under software control†. In the context of this problem, jaw 'velocity' is expressed in mm MU^{-1}. It is assumed that the intensity profile varies linearly between the points, $T(x_i, z_{ref})$, defining the profile. This is a valid approximation as these points are in practice very close together (e.g., 1 mm or less) and the intensity profile can reasonably be considered to vary linearly over such a short distance. The velocity is therefore constant between two adjacent points. Denoting by $\nu^A_{i,i+1}$ the velocity of jaw A between points x_i and x_{i+1}, then

$$\nu^A_{i,i+1} = [x_{i+1} - x_i]/[t_A(x_{i+1}) - t_A(x_i)] \tag{2}$$

with a similar equation defining $\nu^B_{i,i+1}$. These constraints on the velocity therefore require that

$$\nu^A_{i,i+1} \leqslant \nu_{max} \qquad \text{and} \qquad \nu^B_{i,i+1} \leqslant \nu_{max}. \tag{3}$$

Rearranging, these become

$$t_A(x_{i+1}) - t_A(x_i) \geqslant t^{min}_{i,i+1} \tag{4a}$$

and

$$t_B(x_{i+1}) - t_B(x_i) \geqslant t^{min}_{i,i+1} \tag{4b}$$

where

$$t^{min}_{i,i+1} = \frac{1}{\nu_{max}}(x_{i+1} - x_i). \tag{5}$$

Equations (4*a*) and (4*b*) form two sets of linear inequality constraints on the sets of variables $\{t_A(x_i)\}$ and $\{t_B(x_i)\}$. $t^{min}_{i,i+1}$ clearly represents the minimum possible 'time' a jaw can take to get from x_i to x_{i+1}.

† It is anticipated that in practical situations a contributing factor to ν_{max} will be the time response of drive mechanisms and controlling servos. Lowering the output dose rate of the linac would enable effectively higher values of ν_{max} (mm MU^{-1}) to be used, but at the cost of increased treatment times.

Before determining the required jaw motions from the solution of the above equations it is necessary to know the positions at which jaws A and B must start and finish the irradiation. Clearly, jaw A must start from the low-x field edge and jaw B must be at the opposite field edge at the end of irradiation. However, the positions in the field at which jaw B should start and jaw A should stop will depend on the profile being generated. For profiles where the intensity is either decreasing or constant from the low-x field edge, jaw B must also start from this field edge in order to be able to generate this initial shape of the intensity profile. However, if the initial section of the profile is *increasing* in the direction of jaw motion then it is more efficient to start the irradiation with the field partially open—jaw B should be at or as near as possible to the position of the first maximum in the profile, with the initial section of the profile then being generated solely by the motion of jaw A. This is more efficient as it allows the use of wider jaw separations during the irradiation. The actual position from which jaw B will start will be determined by the condition, expressed in equation (4*a*), that jaw A must not be required to exceed ν_{max} in order to generate this initial section of the profile. Jaw B will therefore start from the point nearest to the position of the first maximum such that jaw A is able to reproduce this section of the profile by its motion. This point is determined by considering the quantity, ν_{req}, the velocity jaw A would be required to have in order to generate that section of the profile from x_i to x_{i+1}, i.e.,

$$\nu_{req} = [x_{i+1} - x_i]/[T(x_{i+1}) - T(x_i)].$$

By considering ν_{req} as we move out from the field edge and using the condition that $\nu_{req} \leqslant \nu_{max}$ for acceptable jaw motion, then we can determine the point, $x_{start\ B}$, from which jaw B starts its motion; this point is denoted by the index, $i_{start\ B}$.

Similarly, if the intensity profile is either increasing or constant to the opposite field edge, jaw A must finish its motion at this field edge, while for profiles which are *decreasing* to this edge then the most efficient position for it to stop is at or as near as possible to the final maximum in the intensity modulation. The exact position at which jaw A stops is again determined by the requirement that jaw B must not exceed ν_{max}. This point is denoted by the index, $i_{stop\ A}$.

In determining the collimator motion required to generate the intensity modulation $\{T(x_i)\}$, it is noted that there do not exist unique solution sets $\{t_A(x_i)\}$ and $\{t_B(x_i)\}$ to the governing equations (1*b*), (4*a*) and (4*b*). It is therefore necessary to choose a 'best' solution. This has been defined here to be the most efficient solution—that requiring the minimum cumulative monitor units to irradiate the field. This is equivalent to minimizing the total time required to generate the field at a given dose rate, as cumulative monitor units is then proportional to time. This condition is expressed by the requirement that jaw A takes the minimum number of monitor units to cross the field. The optimal solution is therefore that which minimizes $t_A(x_{stop\ A})$, where $x_{stop\ A}$ is the point at which jaw A stops. This optimization scheme works by maximizing the (varying) separation of the jaws during the irradiation.

The model therefore has the form of an optimization problem subject to sets of linear equality and inequality constraints. It can be expressed fully as follows: find the sets $\{t_A(x_i)\}$ and $\{t_B(x_i)\}$ such that $t_A(x_{stop\ A})$ is minimized, subject to the constraints

$$t_A(x_i) - t_B(x_i) = T(x_i) \qquad i = 1, N \qquad (1b)$$

$$t_A(x_{i+1}) - t_A(x_i) \geqslant t^{min}_{i,i+1} \qquad i = 1, i_{stop\ A} - 1 \qquad (4a)$$

$$t_B(x_{i+1}) - t_B(x_i) \geqslant t^{min}_{i,i+1} \qquad i = i_{start\ B}, N - 1 \qquad (4b)$$

where

$$t_{i,i+1}^{\min} = \frac{1}{\nu_{\max}} (x_{i+1} - x_i). \tag{5}$$

Such linear programming problems are widely documented (see, for example, Gill *et al* 1981) and are readily solved using standard constrained optimization techniques such as the Simplex method. A wide range of standard computer library routines are available for this.

The solution to the optimization problem gives the number of monitor units delivered between the start of irradiation and the time when jaws A and B reach the positions x_i. Collimator motion in terms of the jaw positions as a function of the number of monitor units is then given by the functions $x_A[t_A(x_i)]$ and $x_B[t_A(x_i)]$.

Examples of the application of the algorithm are presented below.

3. Results and discussion

The algorithm above has been implemented on a DEC VaxStation 3100 computer using the Numerical Algorithms Group (NAG) linear programming subroutine E04MBF. Calculation times are typically 1–10 minutes, depending on the complexity of the profile. For a typical profile with 161 points, such as that presented in figure 3(*a*), there are 322 variables and up to 481 constraint equations in the problem.

In order to illustrate the application and results of this algorithm, it is first used to generate the field intensity profile given in figure 2(*a*). This is a relatively simple profile (intensity modulation) across an asymmetrically-collimated field and is useful in illustrating general features of dynamic collimation calculated by this technique. Figures 2(*b*), (*d*), (*f*) and (*h*) show the collimator motion calculated from this profile for $\nu_{\max} = 0.5$, 1, 2 and 3 mm MU^{-1}. (1 mm MU^{-1}, for example, corresponds to a speed of 6.67 mm s^{-1} at a dose rate of 400 MU min^{-1}.) These figures describe the motions of jaws A and B as they sweep across the field during the irradiation; the intensity profile generated is given by the difference, as measured on the abscissa, between the two curves mapping the separate jaw motions. It is seen that the collimator movements have a simple form, reflecting the simplicity of the intensity profile being generated. The smoothest motion is that for the lowest $\nu_{\max}$—this is to be expected, as the allowed range of velocities is smallest for this example. It is also found that the total cumulative monitor units required to irradiate the field (which is proportional to the total time required) decreases with increasing $\nu_{\max}$ as one would expect since the ability to use

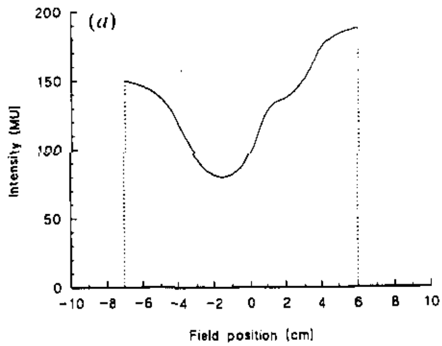

Figure 2. A relatively simple intensity profile to be generated by dynamic collimation is illustrated in (*a*). The collimator motions calculated by applying the algorithm derived in section 2 to this profile are given in (*b*), (*d*), (*f*) and (*h*) for $\nu_{\max} = 0.5$, 1, 2 and 3 mm MU^{-1}, respectively. These figures show the progression of each jaw across the field during irradiation. The corresponding variations of collimator jaw separation during irradiation are given in (*c*), (*e*), (*g*) and (*i*). Each set of graphs has been plotted on the same scale to enable a direct comparison of the figures to be made.

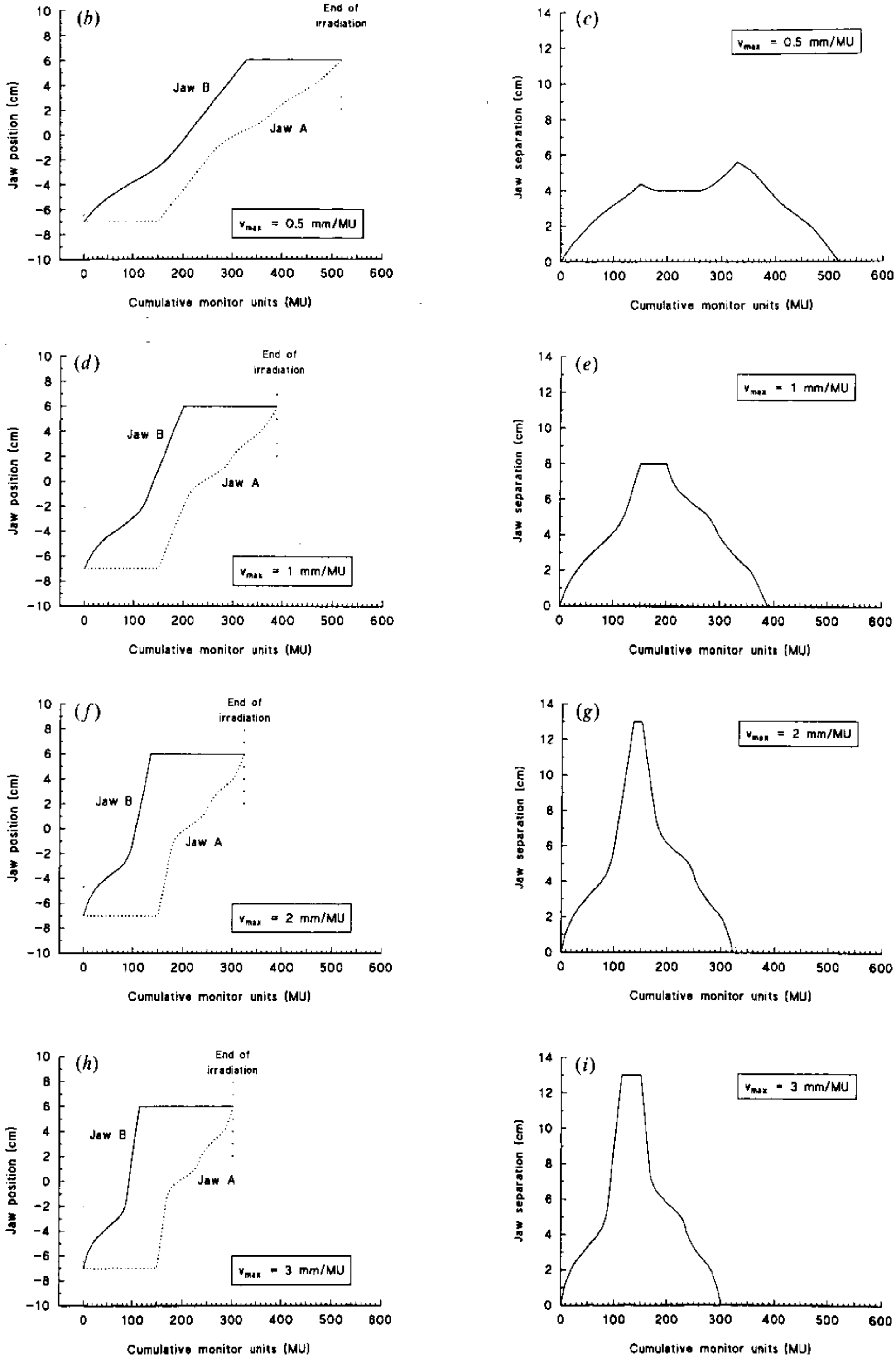

Figure 2. (continued)

higher jaw velocities allows greater flexibility in the motion used to generate the profile, thereby enabling larger jaw separations (and hence shorter irradiation times) to be used. However, it is noted that doubling ν_{max} does not lead to a halving of the irradiation time—this is because the requirement that the jaw movements must generate the specified intensity profile places restrictions on the collimator motion that may be used.

It is apparent that in each case the jaw motion has broadly the same form, independent of ν_{max}. This is because the motion is principally determined by the shape and detail of the intensity profile to be generated. The corresponding variations of jaw separation during irradiation are given in figures 2(*c*), (*e*), (*g*) and (*i*) and in table 1,

Table 1. Minimum, maximum and average jaw separations for the dynamic generation of the intensity profile given in figure 2(*a*).

ν_{max} (mm MU^{-1})	Minimum jaw separation (mm)	Maximum jaw separation (mm)	Average jaw separation (mm)
0.5	0	56	33
1	0	80	44
2	0	130	53
3	0	130	56

which lists the minimum, maximum and average separation for each value of ν_{max} used; the minimum separation is of course zero here since the profile is decreasing at the start of the field and increasing at the opposite field edge, so that the field is closed at the start and at the end of irradiation. It is immediately evident from these figures that the algorithm does not correspond to scanning a narrow 'slit' across the field, and that the aperture is both *variable* and *large.* (Indeed, for $\nu_{max} = 2$ and 3 mm MU^{-1} the separation increases to the full field width during part of the irradiation.) It is this ability of the algorithm to allow the aperture width to vary and so to remain as large as possible throughout the irradiation that gives it its efficiency. A measure of this efficiency is given in table 2, which gives the ratio of total cumulative monitor units required to dynamically generate the profile to the number of monitor units to be given

Table 2. Relative efficiency of the dynamic irradiation technique in generating the intensity profile given in figure 2(*a*). This is expressed by the ratio of total cumulative monitor units required to dynamically generate the profile to the number of monitor units to be given to the profile maximum, and gives the efficiency of the dynamic technique relative to the use of an attenuator.

ν_{max} (mm MU^{-1})	Ratio of total cumulative MU required to dynamically generate field to maximum MU in the intensity profile
0.5	2.76
1	2.06
2	1.72
3	1.60

to the profile maximum. From this table it is seen that, for $\nu_{max} = 0.5$ mm MU^{-1}, the dynamically-collimated field takes a little under three times as long to irradiate as the same field generated using an attenuator (compensator), while for $\nu_{max} = 3$ mm MU^{-1}, the dynamic irradiation takes just 1.6 times as long. These figures are very reasonable since the intensity modulation has to be achieved by the motion of the collimator jaws.

In figure 3(a) a rather more complicated intensity profile is given. The algorithm has been applied for $\nu_{max} = 0.5$, 1, 2, 3 and 5 mm MU^{-1} and the resulting jaw motions for $\nu_{max} = 0.5$, 1, 2 and 5 mm MU^{-1} are given in figures 3(b)-(i). It is evident that the collimator motion required to generate this intensity modulation is more complicated than that for the previous example. This is a reflection of the fact that this modulation is considerably more complex than the previous example. As before, it is found that the smoothest motion occurs for the lowest value of ν_{max}, as one would expect. Similarly, the motion for each ν_{max} is again found to have broadly the same form, independent of ν_{max}, even for this complicated profile. This supports the assertion above that the basic form of the collimator motion is principally determined by the shape and detail of the intensity profile rather than by ν_{max}.

It is seen from figure 3(b) that for $\nu_{max} = 0.5$ mm MU^{-1} this upper limit on the jaw velocity is too small to enable jaw A to generate the first section of the profile (up to the first maximum) by its motion alone. This is because the profile varies too slowly here. Jaw B therefore has to start from the field edge (i.e., the field is closed at the start) rather than from the position of the first maximum in order that jaw A is not required to exceed ν_{max} while generating this section of the profile. (Jaw B is required to start from the field edge because it is the start of the profile that varies too slowly for jaw A to reproduce it.) It is important to note here that it is *slowly* varying sections of the profile that are the most difficult to generate dynamically. Although intuitively one might expect that it would be the rapidly varying sections that would be troublesome, the opposite is in fact the case. This becomes clear when one considers that in order that there be only a small difference in the intensity between these points, then the jaws must move more rapidly between them, and that for smaller intensity differences higher jaw velocities or smaller jaw separation is required. The algorithm presented in this paper is able to generate such slowly varying intensity profiles without exceeding the maximum jaw velocity because the jaws motions are independent. This allows the width of the aperture being scanned to decrease in order to generate slowly varying sections of a profile. This flexibility is not available when only one jaw is moving or when a simple 'close-in' technique is used; in this case it is necessary to reduce the dose rate to increase ν_{max}.

With increasing ν_{max}, jaw B is able to start nearer the position of the first maximum in the intensity profile. This starting position can be clearly seen in figures 3(b), (d), (f) and (h) and is listed in table 3.

Similar comments to those above apply to the position at which jaw A stops (see figures 3(b), (d), (f) and (h) and table 3).

From figures 3(c), (e), (g) and (i) it can be seen that increasing ν_{max} again allows the use of wider jaw separations, and it is this which reduces the time required to irradiate the field; a detailed breakdown of the minimum, maximum and average jaw separations during irradiation for each value of ν_{max} is given in table 4. A measure of the efficiency of the dynamic irradiation of this field is given in table 5, from which it is seen that this more complicated profile requires longer to irradiate than the previous, simple example. This simply reflects the difficulty of generating complicated intensity profiles.

Table 3. Variation with ν_{max} of the positions at which the collimators start and end the dynamic irradiation of the profile in figure 3(*a*).

ν_{max} (mm MU^{-1})	Position within field at which jaw B starts (mm)	Position within field at which jaw A stops (mm)
0.5	−80	70
1	−54	69
2	−52	68
3	−50	68
5	−50	68

Table 4. Minimum, maximum and average jaw separations for the dynamic generation of the intensity profile in figure 3(*a*).

ν_{max} (mm MU^{-1})	Minimum jaw separation (mm)	Maximum jaw separation (mm)	Average jaw separation (mm)
0.5	0	46	30
1	11	65	42
2	12	88	49
3	12	91	52
5	12	94	54

Table 5. Relative efficiency of the dynamic irradiation technique in generating the intensity profile given in figure 3(*a*).

ν_{max} (mm MU^{-1})	Ratio of total cumulative MU required to dynamically generate field to maximum MU in the intensity profile
0.5	3.58
1	2.57
2	2.21
3	2.10
5	2.01

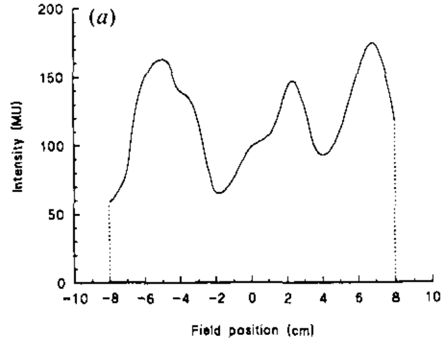

Figure 3. A complex intensity profile having several maxima and minima is given in (*a*). The jaw motions obtained by applying the dynamic collimation algorithm in section 2 are presented in figures (*b*), (*d*), (*f*) and (*h*) for $\nu_{max} = 0.5$, 1, 2 and 5 mm MU^{-1}, with the corresponding variations of jaw separation during irradiation given in (*c*), (*e*), (*g*) and (*i*).

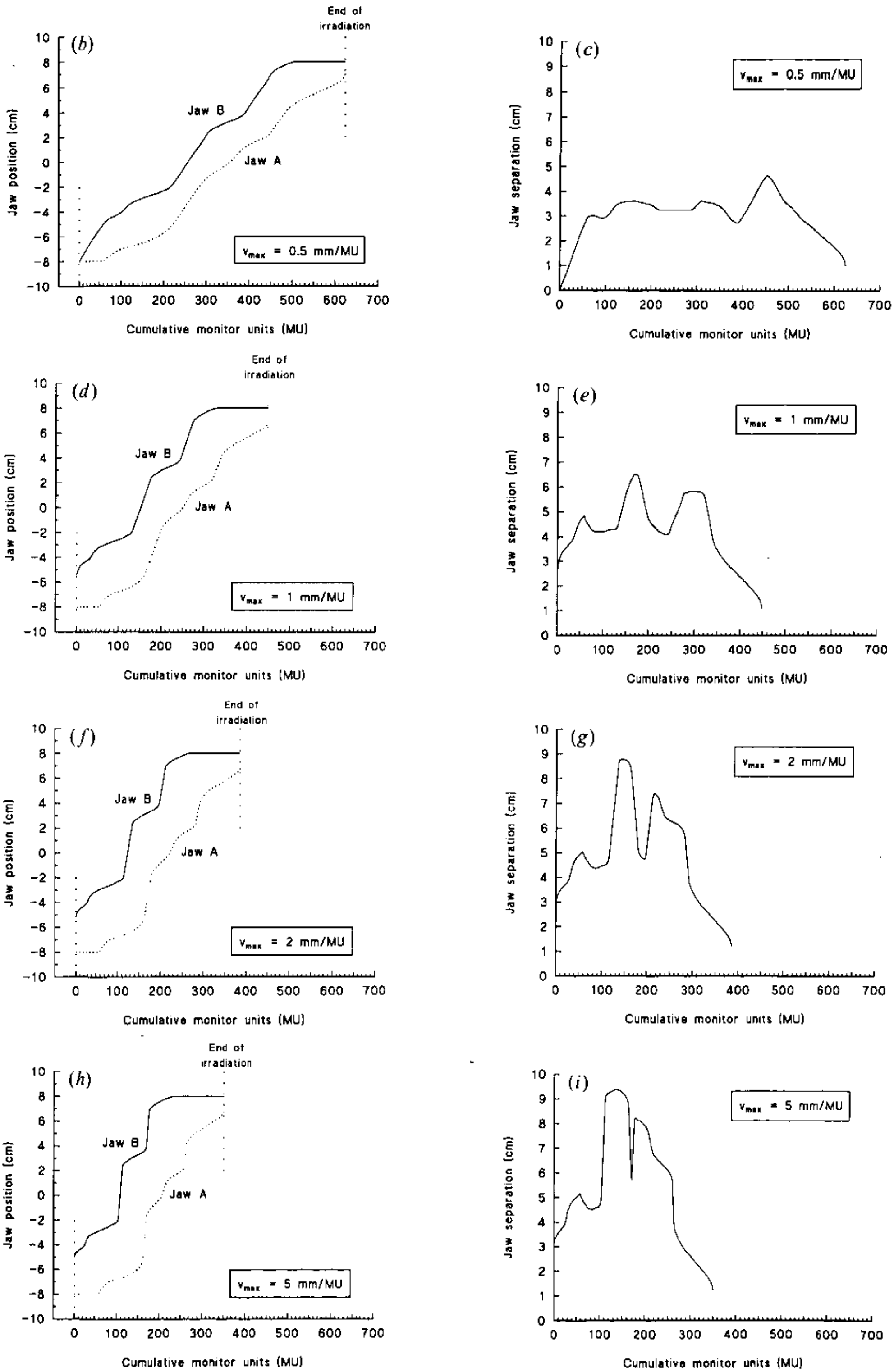

Figure 3. (continued)

4. Extension of the algorithm to intensity-modulated fields for 3D plans

In three-dimensional (3D) conformal planning, the patient outline, internal anatomy and target volume vary from slice to slice within the plan. The required intensity profiles across the fields will therefore also vary between slices.

For such plans to be implemented in a practical manner it is desirable to be able to produce different intensity modulations in different planes simultaneously. This may be achieved by extending the above algorithm to a multileaf collimator (MLC), the motion of each pair of MLC leaves across the field being used to generate a different intensity profile.

The approach presented in section 2.2 needs to be modified slightly for use with an MLC because the different profiles in the field will in general need a different number of monitor units to generate by dynamic collimation, so a solution is to have each pair of leaves closed at the end of their respective motions (with the exception of the pair of leaves generating the profile which takes the longest to treat, which may be left open at the end of irradiation as in the original algorithm). This is achieved in the numerical algorithm by replacing $i_{\mathrm{stop\,A}}$ by N in the set of constraint equations (4a), thereby forcing jaw A to travel to the end of the field and minimizing $t_{\mathrm{A}}(x_N)$.

This modified algorithm has been applied to the two examples presented in section 3. The results for the first profile, figure 2(a), are exactly as before since the profile is increasing towards the far field edge and so jaw A must stop there, as discussed previously.

For the profile in figure 3(a), the dynamic collimation calculated using the modified algorithm is only slightly different from that discussed in section 3. Up to the position of the final maximum the motion is the same as before, and it is only beyond this

Table 6. Variation with $\nu_{\max}$ of the positions at which the collimators start and end the dynamic irradiation of the intensity profile in figure 3(a) for the modified algorithm presented in section 4.

$\nu_{\max}$ (mm MU^{-1})	Position within field at which jaw B starts (mm)	Position within field at which jaw A stops (mm)
0.5	−80	80
1	−54	80
2	−52	80
3	−50	80
5	−50	80

Table 7. Minimum, maximum and average jaw separations for the dynamic generation of the profile in figure 3(a) using the modified algorithm in section 4.

$\nu_{\max}$ (mm MU^{-1})	Minimum jaw separation (mm)	Maximum jaw separation (mm)	Average jaw separation (mm)
0.5	0	46	29
1	0	65	41
2	0	88	48
3	0	91	51
5	0	94	54

Table 8. Relative efficiency of the modified dynamic irradiation technique presented in section 4 for multileaf collimators in generating the intensity profile given in figure 3(a).

ν_{max} (mm MU^{-1})	Ratio of total cumulative MU required to dynamically generate field to maximum MU in the intensity profile
0.5	3.70
1	2.64
2	2.25
3	2.12
5	2.02

point that it is altered so that jaw A stops at the far field edge. Consequently, the algorithm is almost as efficient as before, as can be seen from tables 6–8. As an example of the modified collimation, the jaw motion and separation for $\nu_{max} = 2$ mm MU^{-1} are given in figures 4(a) and (b).

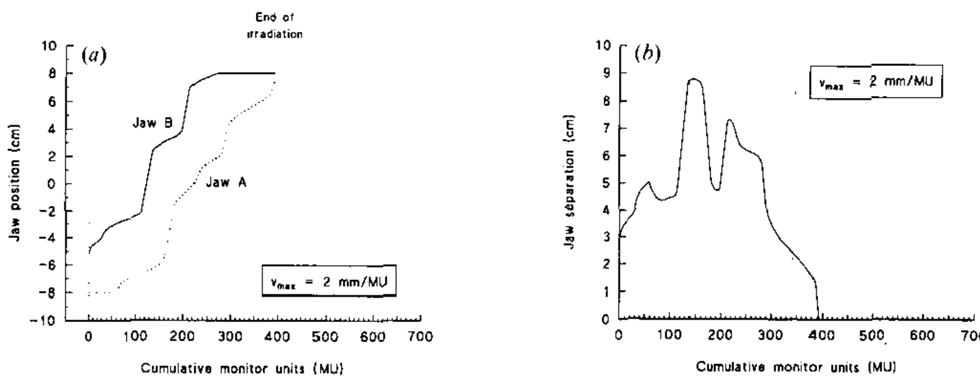

Figure 4. Application of the modified algorithm in section 4 to the generation of the intensity profile in figure 3(a). The jaw motions and variation of jaw separation during irradiation for $\nu_{max} = 2$ mm MU^{-1} are given in (a) and (b), respectively.

As all the profiles across the field are generated simultaneously, the total time to produce all the profiles is simply equal to the time required to generate the most complex one. The algorithm is therefore particularly efficient for 3D conformal plans.

5. The 'close-in' technique

As noted in the introduction, irregular intensity profiles can also be generated using a 'close-in' technique in which the collimator jaws close in towards a single point (or open out from that point), giving a profile with a single maximum. More complex profiles are then generated by successive irradiations of the field (Bjärngard and Kijewski 1976, Källman *et al* 1988).

This approach is here applied to the generation of the profile given in figure 3(a). The profile is divided into segments as shown in figure 5(a); each segment must be irradiated separately using the 'close-in' technique to produce the total intensity profile.

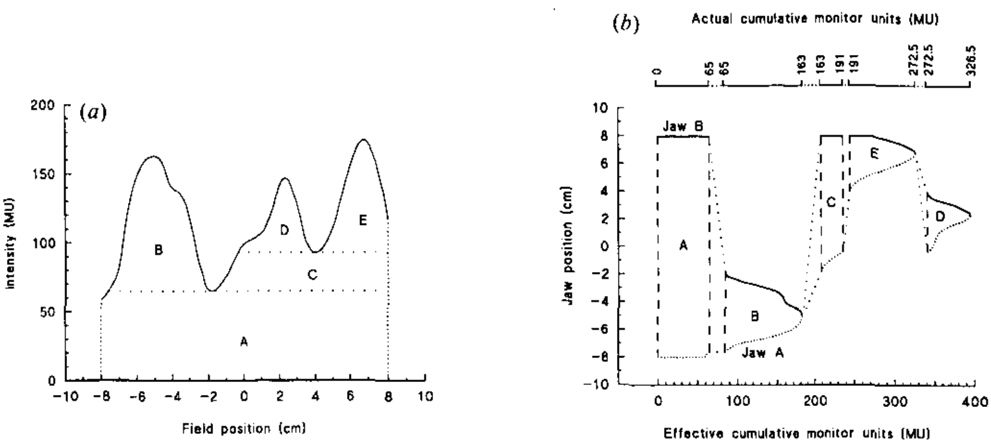

Figure 5. Generation of the second intensity profile (figure 3(*a*)) by a 'close-in' technique. The breakdown of the profile into segments is shown in (*a*), with the resulting jaw motion in (*b*). The 'actual cumulative monitor units' axis is the beam-on time for the treatment. The 'effective cumulative monitor units' gives the effective time it takes to treat the field, assuming that the jaws can move at 5 mm MU^{-1} (ν_{max}) during the move-only periods.

As before, the allowed motion is constrained by the requirement that ν_{max} is not exceeded. For this example, a minimum value of 5 mm MU^{-1} for ν_{max} is necessary for the profile to be generated by the 'close-in' method. ν_{max} can be increased by lowering the output dose rate of the linac.

The resulting jaw motion is given in figure 5(*b*). The dynamic irradiation of each of the five segments can be clearly seen. Between the treatment of each of the field segments there are move-only periods during which the collimators are moving but the beam is off. These are necessary so that the jaws can move to their new positions ready to irradiate the next segment.

The total beam-on time is 326.5 MU (1.87 times the field maximum); the effective 'time' required to treat the field is 395 MU (2.26 times the field maximum), assuming that the jaws move at ν_{max} (5 mm MU^{-1} here) during the move-only periods†. This technique therefore takes a little longer to treat the field than the algorithm developed in section 2, but is more efficient as the total 'beam-on' time is shorter (see table 5).

Such a 'close-in' approach, however, has disadvantages. Unlike the sweep technique developed in this paper, it can only be used if ν_{max} is greater than the minimum jaw velocity required to produce the most slowly-varying part of the profile (5 mm MU^{-1} here). It may therefore be necessary to decrease the dose rate in order to raise ν_{max} to this minimum level, so increasing the actual time taken to treat the field.

More importantly, the 'close-in' approach requires a combination of dynamically-collimated irradiations and move-only periods. While this is not important when generating a single intensity profile, it effectively prevents the use of a computer-controlled MLC to simultaneously produce different profiles at different levels within

† It is possible to express treatment time in monitor units (MU), where it is implicit that the actual time is MU divided by the dose rate. Where there are move-only segments the time for these can still be expressed as monitor units (the product of dose rate and overall treatment time).

For the sake of simplicity it is assumed that the maximum velocities (distance/time) are the same for 'beam-on' and 'move-only' segments. In practice different maximum velocities may be possible but the argument would remain qualitatively the same.

the field, as required for 3D conformal therapy. This is because the move-only periods for each profile, during which the beam must be off, will not in general occur at the same times. Consequently, the profiles need to be produced in succession, increasing the total treatment time (compared to a technique which can generate all the profiles simultaneously) by a factor approximately equal to the number of profiles. This problem does not occur with the algorithm proposed in this paper as the required intensity modulations are produced by a single sweep and there are no move-only periods.

6. Conclusions

An algorithm has been developed to calculate collimator jaw motions to generate irregular field intensity profiles for conformal therapy using computer-controlled linear accelerators. The profile (intensity modulation) is produced using a single sweep of the jaws across the field. The solution found is optimized such that the total cumulative monitor units (and consequently the treatment time) is minimized for the given dose rate, and is shown to provide a powerful and efficient method of generating such intensity-modulated fields. The main characteristics of the required collimator motion are found to depend principally on the shape and structure of the profile rather than the maximum allowed jaw velocity ν_{max}.

A modified version of the algorithm may be used with a computer-controlled multileaf collimator to enable different intensity profiles in different planes of the plan to be produced simultaneously for 3D conformal treatments. The algorithm is particularly efficient in this case as the total time to generate all the profiles is simply equal to the time required to generate the most complex one. This technique provides an efficient practical implementation of conformal therapy plans based on the use of intensity-modulated fields.

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Résumé

Génération de champs modulés en intensité pour la radiothérapie de conformation avec une collimation dynamique.

Les auteurs mis au point un algorithme permettant de calculer les mouvements des machoires du collimateur nécessaires pour générer des champs modulés en intensité, utilisés en radiothérapie de conformation. La technique dynamique permet de générer des profils d'intensité arbitraire en utilisant un seul déplacement unidirectionnel des collimateurs. Les machoires du collimateur sont dotées d'un déplacement indépendant, si bien qu'une ouverture de largeur variable peut être déplacée sur tout le champ. L'algorithme se présente avec propriétés d'un problème d'optimisation sous contrainte, et les déplacements des machoires sont optimisés de telle sorte que le temps de traitement pour le champ, avec un débit de dose donné, soit minimisé. Les auteurs présentent la mise en application et les résultats de cette technique et montrent que cette approche fournit une possibilité pratique efficace pour des plans de traitement en radiothérapie de conformation reposant sur l'utilisation de champs en modulés intensité. Le technique peut être étendue à des plans de traitement tridimensionnels et à des champs utilisant des collimateurs multi-lames contrôlés par ordinateur.

Zusammenfassung

Die Erzeugung von Intensitäts-modulierten Feldern zur konformalen Strahlentherapie durch dynamische Kollimierung.

Ein Algorithmus wurde entwickelt zur Berechnung der Bewegung der Kollimatorbacken zur Erzeugung Intensitäts-modulierter Felder bei der Anwendung in der konformalen Strahlentherapie. Das dynamische Verfahren erlaubt die Erzeugung willkürlicher Intensitätsprofile mit Hilfe einer einzigen in einer Richtung verlaufenden Bewegung des Kollimators. Die Kollimatorbacken können sich unabhängig voneinander bewegen, so daß das Feld von einem Öffnungswinkel variabler Breite abgetastet wird. Der Algorithmus hat die Form eines beschränkten Optimierungsproblems und die Bewegung der Backen ist so optimiert, daß die Behandlungszeit für das Feld bei einer gegebenen Dosisleistung minimiert wird. Anwendung und Ergebnisse dieses Verfahrens werden vorgestellt und es wird gezeigt, daß so eine effiziente praktische Umsetzung der Bestrahlungspläne bei der konformalen Strahlentherapie unter Verwendung von Intensitäts-modulierten Feldern erreicht werden kann. Das Verfahren kann auch für 3D Bestrahlungspläne und -felder verwendet werden, wenn man rechnergesteuerte Lamellenkollimatoren benutzt.

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