PLANNING, DELIVERY, AND QUALITY ASSURANCE OF INTENSITY- MODULATED RADIOTHERAPY USING DYNAMIC MULTILEAF COLLIMATOR: A STRATEGY FOR LARGE-SCALE IMPLEMENTATION FOR THE TREATMENT OF CARCINOMA OF THE PROSTATE

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Purpose: To improve the local control of patients with adenocarcinoma of the prostate we have implemented intensity modulated radiation therapy (IMRT) to deliver a prescribed dose of 81 Gy. This method is based on inverse planning and the use of dynamic multileaf collimators (DMLC). Because IMRT is a new modality, a major emphasis was on the quality assurance of each component of the process and on patient safety. In this article we describe in detail our procedures and quality assurance program.

Methods and Materials: Using an inverse algorithm, we have developed a treatment plan consisting five intensity-modulated (IM) photon fields that are delivered with DMLC. In the planning stage, the planner specifies the number of beams and their directions, and the desired doses for the target, the normal organs and the “overlap” regions. Then, the inverse algorithm designs intensity profiles that best meet the specified criteria. A second algorithm determines the leaf motion that would produce the designed intensity pattern and produces a DMLC file as input to the MLC control computer. Our quality assurance program for the planning and treatment delivery process includes the following components: 1) verification of the DMLC field boundary on localization port film, 2) verification that the leaf motion of the DMLC file produces the planned dose distribution (with an independent calculation), 3) comparison of dose distribution produced by DMLC in a flat phantom with that calculated by the treatment planning computer for the same experimental condition, 4) comparison of the planned leaf motions with that implemented for the treatment (as recorded on the MLC log files), 5) confirmation of the initial and final positions of the MLC for each field by a record-and-verify system, and 6) in vivo dose measurements.

Results: Using a five-field IMRT plan we have customized dose distribution to conform to and deliver 81 Gy to the PTV. In addition, in the overlap regions between the PTV and the rectum, and between the PTV and the bladder, the dose is kept within the tolerance of the respective organs. Our QA checks show acceptable agreement between the planned and the implemented leaf motions. Correspondingly, film and TLD dosimetry indicates that doses delivered agrees with the planned dose to within 2%. As of September 15, 1996, we have treated eight patients to 81 Gy with IMRT.

Conclusion: For complex planning problems where the surrounding normal tissues place severe constraints on the prescription dose, IMRT provides a powerful and efficient solution. Given a comprehensive and rigorous quality-assurance program, the intensity-modulated fields can be efficaciously and accurately delivered using DMLC. IMRT treatment is now ready for routine implementation on a large scale in our clinic. © 1997 Elsevier Science Inc.

Radiotherapy, Prostate cancer, Intensity modulation, Dynamic multileaf collimator, DMLC.

INTRODUCTION

In the management of patients with carcinoma of the prostate, the aims of the radiation treatment are to treat the localized disease to an adequate dose but to keep the dose to the neighboring rectum and bladder to within their respective tolerance. Generally doses in the range of 65 to 75 Gy are used for the treatment. However, based on the hypothesis that higher doses may provide better control of localized prostate disease, currently there are dose escalation trials underway at various institutions, including ours (9, 13, 14, 24–26, 30).

At our institution, the planning target volume (PTV) for radiotherapy of the prostate includes portions of the rectal and bladder walls. As was reported previously, in those treatment with our standard six-field 3D conformal plan to
75.6 Gy, the prescription dose was delivered to the maximum isodose level covering the PTV. The full dose was given to the overlap between the rectum and the PTV, and to that between the bladder and the PTV (13, 30). When the dose was escalated to 81 Gy, there was concern that the same beam arrangement, delivering the full dose to a portion of the rectum, may lead to unacceptably high incidence of rectal complications (1, 12). Thus, the total dose of 81 Gy was given in two phases (30). The first phase consisted of the standard six-field conformal plan delivering 72 Gy in 1.8 Gy fractions, followed by a 5 × 1.8 Gy boost with six to eight lateral and posterior-lateral oblique wedged fields in which shields were placed for the rectum. To obtain acceptable dose distribution for the boost treatment, the beam weights and the wedge angles often required repeated adjustment, and was therefore labor-intensive. An important constraint on the combined dose distribution from the entire treatment course was that <30% of the rectal wall was to receive 76 Gy or higher dose (30). A total of 61 patients have been treated using the beam arrangement described above.

In October 1995, intensity-modulated radiation treatment (IMRT) was implemented at Memorial Sloan Kettering Cancer for the treatment of the prostate (16). An inverse-planning algorithm was used to produce optimized intensity profiles for the designated treatment fields (2, 3, 22). The intensity-modulated beams were then delivered using DMLC following the method described by Spirou and Chui (27). In that phase of implementation, IMRT was used for the 5 × 1.8 Gy boost, after the primary treatment of 72 Gy. The IMRT boost was delivered with the same lateral and posterior-lateral beam angles as the manual planned boost described above, so as to introduce improvement increment by increment without incurring radical changes in our treatment protocol. The efficacy of this modality, the efficiency in the planning phase, and ease of treatment delivery has been documented (16).

As we have previously noted, the use of IMRT for only the boost treatment can not reveal the full potential of this modality (16). Thus, we have developed a five-field technique by which IMRT is used for the entire treatment course of 81 Gy, and have implemented this approach for the patient treatment since April 1996. This article describes the established process of IMRT and our experience in treating about eight patients to date. The QA (quality assurance) procedures that are used to assure that the correct dose is delivered safely are described. These tests are carried out by the planner and then checked by a senior physicist. After we have collected sufficient QA data, we may relax some of the QA procedures. As we gain more experience in the use of IMRT, plans are underway to implement it on a wider scale for the clinical use.

Methods and Materials

Immobilization, simulation and CT scanning

The patient is immobilized in a prone position with a thermoplastic mold. A simulation is then carried out to select the treatment isocenter. A pair of orthogonal radiographs is taken for isocenter localization. Additional films are taken at the following treatment beam angles: posterior (0°), right posterior oblique (75°), right anterior oblique (135°), left anterior oblique (225°), and left posterior oblique (285°). Using the wall-mounted alignment lasers the triangulation points for isocenter are tattooed on the patient’s skin.

For the treatment planning, volumetric CT data are obtained by scanning the patient in the treatment position as described by Leibel et al. (13). Radiopaque markers are taped at the tattoo marks to highlight the isocenter triangulation points on the CT scans. The patient is scanned from the lower abdomen to the thighs. In the central 10 cm region, where the prostate and seminal vesicles are located, 5-mm spacing and thickness in used; 10-mm thickness and spacing is used elsewhere.

CT data transfer and digitally reconstructed radiographs

The volumetric CT data set is transferred to the MSKCC treatment planning system (18). The PTV (10) and the normal tissues are outlined interactively on a video monitor. The clinical target volume (CTV) (10) includes the prostate and the seminal vesicles. A 1-cm margin is added around the CTV to define the PTV. However, at the boundary between the anterior rectal wall and the prostate, a 0.6-cm margin is used (13). We have found these margins to be adequate to provide good clinical response in patients treated under Phase III dose escalation trial (30). The contoured normal tissues include the bladder wall, rectal wall, small bowel, femurs, pelvic bone, and the outer surface of the skin.

On the 3D treatment-planning system, the radiopaque markers, visible on the CT scans, are used to locate the isocenter. A pair of digitally reconstructed radiographs (DRR) is generated for the orthogonal posterior and lateral beams for comparison with the corresponding simulation films. Based on this comparison, the location of the isocenter is adjusted on the treatment-planning system as required.

Inverse planning

The various steps of treatment planning and delivery for IMRT, and the associated quality assurance programs, are shown schematically in Fig. 1. The steps are numbered in the sequence in which they are carried out. The first step is the optimization of the intensity of the five treatment beams (15 MV, with beam angles given previously). A modified version of the inverse-planning program developed by Bortfeld et al. (2, 3, 22) is used. An important modification was

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the inclusion of the effect of scattered radiation in the iterative optimization (6, 16). The aim of the optimization is to minimize the sum of quadratic differences between desired and computed dose distributions (23, 29). The parameters of ray weight optimization based on inverse technique thus include dose limits for each critical anatomical structure relative to the target volume, the penalty for exceeding the limits, relative dose values in the regions of overlap, and penalty for deviating from the specified dose. The optimization process balances various requirements of the dose distribution, and it should be noted that the parameters specifying limits of relative dose to the critical structures and the relative dose to the overlap regions are different from the actual dose values desired. In this case, the parameters that produced the desired dose distribution are: a uniform dose (100%) to the PTV, dose limit of 40% for the rectum, and 58% for the bladder. In the overlap region between the PTV and the rectum, the dose constraint is set to 88% for the rectum; and in the overlap region between the bladder and the PTV to 98%. A higher priority (5 to 1) is given to the critical organs in the overlap regions.

On average, the optimization is completed in 5–10 min. The intensity profiles of the IM beams which best satisfy the specified conditions are produced and the associated dose distribution are calculated (step 2). The dose distribution for an intensity-modulated field is calculated in two steps. First, the dose is calculated for the corresponding open field without considering intensity modulation. The algorithm used for this calculation is primarily based on empirical data, such as measured depth doses and crossbeam profiles. Second, the effect of intensity modulation, i.e., arbitrary intensity distribution, is accounted for by calculating correction factors, which are then applied to the dose calculated for the open field. Further details about the method of dose calculation are given in appendix A. Upon approval of the treatment plan by the attending physician, the process proceeds to the next step.

Also generated in this step are Beam’s-eye-view (BEV) DRRs, onto which the “fluence apertures” are projected. The fluence aperture of each IM field is specified to encompass the area with intensity >1% of the maximum. The fluence apertures are then transferred to the simulation radiographs by comparing the latter with the DRRs. As shall be discussed, the fluence apertures compare favorably with the portal films generated in IMRT delivery.

The DMLC and R & V files
To deliver the intensity-modulated beams, we have adopted the “sliding-window” method, as developed by Spirou and Chui (27). In this method, during the movement of the MLC leaves, at least one leaf of each pair is at the maximum allowable speed. This results in maximum efficiency: the monitor units (MUs) to deliver the dose are kept to a minimum. Based on the optimized intensity profiles, a computer algorithm determines the leaf positions as a function of MU for each beam, producing the “DMLC” file.
(step 3). The effect of the rounded leaf edge and the transmitted radiation through the leaves (28) are taken into consideration. The DMLC file is then transferred, via a floppy disk, to the MLC control computer on a Clinac 2100C\(^2\) (step 4). In addition, a record-and-verify (RV) file, containing information on the initial and final positions of each leaf, is electronically transmitted to the MSKCC RV system.

**IM beams from DMLC file and resultant dose distribution**

To ensure that step 3 of the process did not introduce artifacts or unacceptable approximations, an independent program produces IM beams from the DMLC files (step 5), and these beams are used to generated dose distributions for comparison (step 6) with those produced by inverse planning in step 2.

**QA of DMLC delivery—before and during treatment**

Prior to the delivery of each IMRT field during a treatment session, the RV computer checks that the starting leaf positions are correct, and that the other machine parameters (including the gantry angle, the collimator angle, the field size, and MU) are also properly set (step 14). At the conclusion of dose delivery from each field, the final leaf positions are also verified.

During treatment delivery with DMLC, the MLC control computer records the positions of the leaves every 55 ms and assures that they are within a preset tolerance (chosen to be 2 mm, as discussed later). If the leave positions are within tolerance, the radiation delivery continues; otherwise, the beams pulses are "witheld" until the condition becomes satisfied. The record of the leaf motions as a function of MU is stored in DMLC log file (step 7).

As an additional safety precaution, at least for the first 10 patients, we have adopted a pretreatment check of DMLC performance. Prior to the first treatment of each patient, the therapist performs a practice run of each treatment field. The DMLC log files are then compared with the DMLC files, using a computer algorithm, to ensure that the actual motion of the leaves agrees with that planned to within the preset tolerance (step 8).

**Dosimetric verification of IMRT**

To ensure that the IM beams delivered the same dose as those derived by the inverse planning method, a dose distribution is generated for a flat phantom using the optimal beam fluence determined for the patient, and compared with the measured dose distribution in the same geometry. For the film measurements Kodak XV2\(^3\) film is used. For the individual field comparison the film is exposed perpendicular to the beam. A dose–response curve for the film using the same depth and approximate field size as the measured data for the patient's field is obtained. This ensures that the scatter contribution for the calibration films is comparable to the patient's films. With careful control of film processing conditions, our film dosimetry is accurate to within 2%. The film dosimetry measurements at a depth of 15 cm in a flat phantom are carried out (step 9) and compared with the dose distribution calculated by the treatment-planning system for the same geometry (step 10). This comparison is carried out prior to the patient's first treatment.

On the first day of the patient's treatment, a physicist or a dosimetrist is present to perform *in vivo* TLD (thermoluminescent dosimeter) measurements. During the treatment, for the LPO, RPO, and, if convenient for the POST fields, the TLDs are placed at the central axis of the beam on the patient's skin, and bolused with 3-cm thick tissue-equivalent material for electronic buildup. The measured entrance doses are compared with those calculated for the actual conditions.

**Comparison of portal film with simulation film and BEV-DRR**

Prior to the actual treatment the location of the isocenter is verified by comparing orthogonal localization port films with similarly obtained simulation films. Then, localization port films are obtained for each IM field (step 11), with the MLC set to the extreme positions of the DMLC motion (maximal DMLC aperture), that is, the trailing leaves are positioned at their "start" position and the leading leaves are positioned at their "stop" position. The port films are compared with the corresponding DRR superimposed with the fluence aperture (step 12). This procedure verifies that the radiation is directed properly, relative to the bony anatomy.

**RESULTS**

As of September 15, 1996, eight patients have completed the 81 Gy IMRT treatment. The process, described in Methods and Materials, has proven to be efficient and reliable. Our experience and findings to date on the various components of the IMRT process is described below.

**Dose distribution and DVH from inverse planning**

For all the patients in this study, the inverse planning algorithm produced satisfactory dose distribution and PTV coverage, with critical organ dose–volume parameters within the respective tolerance. Because there were no patient selection based on CT anatomical data, it is likely that this approach will produce satisfactory treatment plans for most patients treated to 81 Gy.

To illustrate the results we present the dose distribution information of one patient treated with IMRT. The isodose distributions (in units of Gy), superimposed on the PTV, the rectum, and the bladder are shown in Fig. 2 in the transverse, coronal, and sagittal planes. The 81 Gy isodose line encloses the PTV, except in the overlap between the PTV

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\(^{2}\) Varian Associates, Palo Alto, CA.

\(^{3}\) Eastman Kodak Company, Rochester, NY.
Fig. 2. Isodose distributions in three mutually perpendicular planes: (a) transverse, (b) coronal, and (c) sagittal. The isodoses are in units of Gy. The planning target volume (yellow) and rectum (magenta) and bladder (orange) are also shown.

As was previously reported, using our standard six-field conformal plan, we have treated over 300 patients to 75.6 Gy with acceptable level of organ toxicity (30). The DVHs for those plans showed that about 20–30% of the rectum received 75.6 Gy or higher; therefore, this dose limit was chosen as a reference for our dose escalation to 81 Gy. For the illustrative patient, a comparison of the rectal DVH for the six-field 75.6 Gy plan and the inverse method designed 81 Gy plan is given in Fig. 3b. The two DVHs are very similar, with the 75.6 Gy plan having a slightly larger volume in the 70–75 Gy region, and a smaller volume in the 20–40 Gy region. Thus, the 81 Gy inverse plan was considered satisfactory relative to rectal dose volume parameters. For the other seven patients treated with the IMRT 81 Gy plan, the DVHs were similarly acceptable.

To further characterize the relative merits of the respective treatment plans described in the last paragraph, we estimated the normal tissue complication probability (NTCP) of the rectum using the Lyman's model (17), the parameters for the end point of severe proctitis and necrosis (5), and the histogram reduction scheme of Kutcher et al. (11). The calculated rectal NTCP was about 2% for both plans. The estimated NTCP for the other patients ranged from 1 to 3.5%.

Similar comparison of the DVHs for the bladder wall is shown in Fig. 3c. A small volume (about 5%) of the bladder wall received up to 83 Gy in the IMRT plan, compared to 76 Gy for the six-field 75.6 Gy plan. However, the calculated NTCP for symptomatic bladder contracture and volume loss (5) was negligible for both plans. As for the femurs (Fig. 3d), the dose was considerably lower in the IMRT plan than that for the 75.6 Gy plan.

Figure 3a shows a comparison of the DVHs for the PTV. The D\textsubscript{95} (at least this dose is received by 95% of the PTV) is 78 Gy for 81 Gy IMRT plan, and 74 Gy for the six-field 75.6 Gy plan. To assess the clinical significance of such dose increase, we estimated the tumor control probabilities (TCPs) using the model of Goitein (8) and the parameters previously described by Mohan et al. (21). The calculated TCP was 90% for the 81 Gy IMRT plan, and 83% for the six-field 75.6 Gy plan.

Profiles of intensity-modulated beams

The BEV intensity profiles of the five IM beams produced by the inverse planning algorithm for the illustrative patient are given in Fig. 4. Each beam exhibits modulated fluence profile, with areas of dose diminution corresponding to regions subtended by the rectum in the BEV. The profiles of the IM beams for the other patients are similar; variations exist due to interpatient differences in the shapes and sizes of the structures and their geometrical relationship.

Independent dose calculation with DMLC files

To ensure that the DMLC files will generate the desired dose distribution, an independent algorithm derives IM beams from the DMLC files. Then, dose distribution is calculated using the derived IM beams on the 3D treatment-planning computer and compared to the original pattern. Table 1 shows the comparison of the isocenter dose of the original and the “check” dose distributions, for the illustrative patient. Similarly, excellent agreement was observed for other regions of the treatment volume for this patient, and for the other seven patients. It follows that comparison of the DVHs for the PTV, bladder wall, and rectal wall yield similarly excellent agreement.
Dosimetry verification

One aspect of dosimetric verification was film measurement in a polystyrene phantom. Figure 5a shows the comparison of the measured dose distribution (for the LAO field of the illustrative patient) with that calculated by the treatment planning computer for the measurement condition. The calculated isodose curves (solid lines) are almost indistinguishable from the measured ones (dashed lines). Excellent agreement was also obtained between the measured and calculated crossfield dose profiles in both the selected x and y directions (Fig. 5b and c, respectively).

Results from TLD measurement for the selected fields, compared to calculated results are presented in Table 2. For most of the cases the measured and the calculated doses are within 5%.

QA of DMLC performance

In pretreatment QA of DMLC performance for each of the field a log file was generated that contains a log of MLC position as a function of MU for comparison with the planned leaf motion. Table 3 shows an example of the result of a comparison. The first column shows the dose fraction at which there was a discrepancy exceeding the tolerance of 2 mm. A "1" in the second column indicates that the control computer issued a command to momentarily withhold beam pulses. The third column shows whether the beam was On ("1") or Off ("0"). (Note actually beam-off occurs a time after a withhold command is issued.) The leaf number, the planned position, and the actual positions are also listed. The last column (severity) provides a visual cue for the magnitude of discrepancy: an * indicates a deviation of 3-4 mm, ** of 4-5 mm, *** of 5-6 mm, and so on. On average, for each DMLC field there were two *, one ** deviation, less than one *** deviation, and none more severe.

To ensure that such leaf position errors do not lead to unacceptable dose inaccuracy, we have evaluated the delivered dose with film and ion chamber dosimetry for tolerance settings ranging from 0.1 to 5 mm. The delivered dose was constant for tolerance settings > 2 mm, and a dose difference of about 0.5% was observed between
Fig. 4. The intensity profiles in the isocentric plane for the five treatment beams: (a) left anterior oblique, gantry angle = 225°; (b) left posterior oblique, gantry angle = 285°; (c) posterior, gantry angle = 0°; (d) right posterior oblique, gantry angle = 75°; (e) right anterior oblique, gantry angle = 135°.

Thus, DMLC performance as exemplified by the results of Table 3 was judged to be acceptable.

DISCUSSION

IMRT, in giving the planner more degrees of freedom, is a new and powerful technique to customize the 3D dose distributions of external beam photon radiotherapy. Thus far, we have used it to plan and implement 81 Gy treatments for patients with prostate cancer and have found it efficacious. Plans are underway to use this method for dose escalation to 86.4 Gy (23).

The methods of IMRT treatment planning and dose delivery differ in certain aspects from those of conventional methods. For the treatment of patients with prostate cancer, the initial steps of CT data acquisition, contour delineation of the PTV, and critical organs are
similar for the two methods. Then, for the standard six-field conformal treatment, the Autoplan (2) option of our 3D treatment-planning system is invoked, whereby the six radiation ports are automatically applied from the prespecified gantry angles, the apertures designed, dose distributions calculated, and isodose data presented in three orthogonal planes, and dose-volume histograms generated (4, 15). For the five-field IMRT plan, the inverse planning algorithm is called upon to design the intensity profiles for each field (15, 22). As it turns out, for patients treated to 75.6 Gy, the time for running the Autoplan, and the inverse algorithm is similar and amounts to 5 to 10 min. However, to plan a patient from start to finish takes approximately 10 h by either method. To plan a patient by traditional method for a prescription dose of 81 Gy, a two-phase planning (72 Gy primary treatment + 9 Gy boost) is necessary. In designing the boost for the two-phase plan, the planner needs to adjust the wedge angles and the beam weights iteratively to achieve an acceptable dose distribution, and the process could take up to additional 10 to 12 h. In contrast, the IMRT plan, in using the same five-field for the entire treatment, involves only one planning session and, therefore, is extremely labor-saving compared to the two phase manual plan.

Delivery of the IMRT plan with DMLC is also very efficient. Once the patient has been set up and the radiotherapist exits the room, on average the total time for treatment with IMRT is 5 to 6 min for the five-treatment fields. This is comparable to, albeit slightly longer than, that needed to deliver six static MLC fields due to the larger number of MU needed in the IMRT treatment. For the IMRT plan the beam-on times, to deliver the prescription dose of 1.80 Gy, range from 90 to 200 MU for each treatment field. Total monitor units for all five fields is approximately 700 MU, compared to ~300 MU for the six-field MLC plan. So the MUs for the IMRT plans are 2 to 2.5× that required for the static MLC fields, but comparable to the static wedged fields with 40–50% wedge transmission factor. Thus, the total body dose from leakage is similar to the fields using typical 45–60° wedges, and MLC used for IMRT would not be expected to produce excess neutrons relative to the wedges and blocks it replaces.

In this initial implementation of IMRT using DMLC,

<table>
<thead>
<tr>
<th>Treatment beam</th>
<th>Original plan dose (%)</th>
<th>Independent-check dose (%)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1LA0</td>
<td>22.1</td>
<td>22.3</td>
<td>0.9</td>
</tr>
<tr>
<td>2LPO</td>
<td>20.6</td>
<td>20.7</td>
<td>0.5</td>
</tr>
<tr>
<td>3POST</td>
<td>17.9</td>
<td>18.0</td>
<td>0.6</td>
</tr>
<tr>
<td>4RPO</td>
<td>20.8</td>
<td>20.8</td>
<td>0.0</td>
</tr>
<tr>
<td>5RAO</td>
<td>22.3</td>
<td>22.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>103.8</td>
<td>104.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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Fig. 5. Comparison of the calculated dose (solid lines) and measured dose (dashed lines) for the intensity-modulated LAO (225°) beam. (a) The dose distributions (in cGy) are for a plane at the isocenter, at 15 cm depth in a homogeneous polystyrene phantom. (b) The cross field profile at x = 0 cm. (c) The cross field profile at y = −1.5 cm.
After we gain confidence in the reliability of program is mandatory to ensure that the dose is delivered safely and accurately. However, other procedures will be computerized and automated, for example, comparison of DMLC log file with planned DMLC motion. Other quality assurance procedures, for example, DV of start and stop MLC positions and comparison of weekly post film with DRR, will be continued. The aim is to develop a QA program that is both stringent and efficient. Last, the possibility of using the on-line imagers for dosimetric verification is being studied.

In summary, the IMRT method offers much potential in providing improved treatment. With the development of the new computer controlled treatment machines with DMLC, it is now possible to deliver such treatments reliably and efficiently. However, a comprehensive QA program is mandatory to ensure that the dose is delivered safely and accurately.

### REFERENCES


**APPENDIX A**

**Dose calculation algorithm**

Dose distribution resulting from an intensity-modulated field is calculated in two steps. First, dose is calculated for modulation. Second, the effect of intensity modulation is accounted for by calculating correction factors, which are then applied to the doses calculated for the open field. Each of the two steps are described below.

**Dose calculation for open field.** The dose for the open field, $D_{\text{open}}(x,y,d)$, is calculated as:

$$D_{\text{open}}(x,y,d) = MU \cdot \text{OF}(w \times h) \cdot \text{TMR}(w \times h; d) \cdot \text{OCR}(w \times h; x, y, d) \cdot G,$$  

where $MU$ is the beam-on time: $\text{OF}(w \times h)$ is the output factor at $d_{\text{max}}$ for a field of size $w \times h$. The TMR term is the tissue-maximum ratio measured along the central axis of the beam, and $d$ is the equivalent depth that accounts for patient inhomogeneity correction. The OCR term accounts for off-axis corrections including effects such as "horns," variation of beam quality with off-axis distance, and penumbra region near the edge of the field. A detailed description of OCR can be found in reference (7). The term $G$ represents the inverse-square factor for divergent beams. The values of $\text{OF}$, TMR, and OCR are all interpolated from empirical data that were acquired for a standard set of field sizes and depths spanning the clinically applicable range.

**Correction factors.** The correction factors are calculated at each point as the ratio of the dose resulting from an 'idealized' intensity-modulated field to that from a corresponding "idealized" open field. The dose due to an "idealized" intensity-modulated field is computed as:

$$D'_{\text{int-mod}}(x,y,d) = \int \int \int \phi(x',y')k(x-x',y-y',d)dx'dy',$$  

where $\phi(x,y)$ is the intensity distribution and $k(x,y,d)$ is the pencil beam kernel at depth $d$ in the medium. The pencil beam kernels for a given beam energy may be obtained by Monte Carlo simulations (19) using a realistic photon spectrum (20). The limits of integration, $w$ and $h$, are the field size for the open field.

Similarly, the dose due to a corresponding "idealized" open field is calculated as

$$D'_{\text{open}}(x,y,d) = \int \int \int U(x',y')k(x-x',y-y',d)dx'dy',$$  

where $U(x,y)$ is the intensity distribution.
where \( U(x,y) \) is the uniform intensity distribution describing the open field. In practice, these convolutions are carried out using fast Fourier transforms and, therefore, are computationally very efficient. The correction factor at each point is then the ratio

\[
\left[ \frac{D'_{\text{int-mod}}(x,y,d)}{D'_{\text{open}}(x,y,d)} \right].
\]

Note that the doses calculated by expressions (2) and (3) are based on first principles and are only valid for "idealized" beams, which differ from clinical beams in a number of ways. Briefly, the "idealized" beams are parallel (rather than divergent) because the kernels used in the convolutions are from parallel pencil beams; the fluence function \( U(x,y) \) is uniform, whereas a clinical beam may have "horns"; and beam quality is assumed to be constant over the field rather than variable with off-axis distance. These approximations, however, are acceptable because they are used to calculate ratios that account for the effect of arbitrary intensity distribution relative to that of uniform distribution.

Finally, the dose from a clinical intensity-modulated field \( D_{\text{int-mod}} \) is calculated by applying the correction factors to doses calculated for the open field, \( D_{\text{open}} \)

\[
D_{\text{int-mod}}(x,y,d) = D_{\text{open}}(x,y,d) \left[ \frac{D'_{\text{int-mod}}(x,y,d)}{D'_{\text{open}}(x,y,d)} \right].
\]