## AAPM REPORT NO. 72

# BASIC APPLICATIONS OF MULTILEAF COLLIMATORS

**Report of Task Group No. 50**
**Radiation Therapy Committee**

Arthur Boyer, Ph.D.
Peter Biggs, Ph.D.
James Galvin, D.Sc.
Eric Klein, M.Sc.
Thomas LoSasso, Ph.D.
Daniel Low, Ph.D.
Katherine Mah, M.Sc.
Cedric Yu, D.Sc.

July 2001

Published for the
American Association of Physicists in Medicine
by Medical Physics Publishing

DISCLAIMER: This publication is based on sources and information believed to be reliable, but the AAPM and the editors disclaim any warranty or liability based on or relating to the contents of this publication.

The AAPM does not endorse any products, manufacturers, or suppliers. Nothing in this publication should be interpreted as implying such endorsement.

Further copies of this report ($15 prepaid) may be obtained from:

Medical Physics Publishing
4513 Vernon Blvd.
Madison, WI 53705-4964
Telephone: 1-800-442-5778 or
608-262-4021
Fax: 608-265-2121
Email: mpp@medicalphysics.org
Web site: www.medicalphysics.org

International Standard Book Number: 1-888340-30-4
International Standard Serial Number: 0271-7344



Published by Medical Physics Publishing
4513 Vernon Blvd., Madison, WI 53705-4964

Printed in the United States of America

## TABLE OF CONTENTS

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of drawings and technical data from General Electric Medical Systems, Elekta Oncology Systems (formerly Philips Oncology Systems), Siemens Medical Systems, and Varian Oncology Systems.

A portion of this report has been previously published as sections 12.1.1 and 12.1.2 in *The Modern Technology of Radiation Oncology*, Jacob Van Dyk (ed.), © 1999 Jacob Van Dyk, pages 438–448. Reprinted by permission of Jacob Van Dyk and Medical Physics Publishing.

## ADDENDUM

Varian MLC Options

| (all dimensions in cm) | **Standard 52 leaf** | **Standard 80 leaf** | **Millennium 52 leaf** | **Millennium 80 leaf** | **Millennium 120 leaf** |
|---|---|---|---|---|---|
| Number of leaves | 52 | 80 | 52 | 80 | 120 |
| MLC Plan: Max Retract Position | 20.1 | 20.1 | 20.1 | 20.1 | 20.1 |
| MLC Plan: Max Extend Position | –16.0 | –16.0 | –20.1 | –20.1 | –20.1 |
| Leaf span | 14.5 | 14.5 | 15.0 | 15.0 | 15.0 |
| Leaf width | All pairs: 1.0 | Pairs 1 & 40: 1.5<br>All others: 1.0 | All pairs: 1.0 | Pairs 1 & 40: 1.4<br>All others: 1.0 | Pairs 1 & 40: 1.4<br>Pairs 2–10 &<br>51–59: 1.0<br>All others: 0.5 |
| Source to leaf bottom | 53.6 | 53.6 | 53.8 | 53.8 | 53.8 |
| Source to block tray | 65.4 | 65.4 | 65.4 | 65.4 | 65.4 |
| Source to gantry housing | 57.9 | 57.9 | 57.9 | 57.9 | 57.9 |
| Maximum height of blocks | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 |
| Maximum shapable field | $26 \times 40$ | $40 \times 40$ | $26 \times 40$ | $40 \times 40$ | $40 \times 40$ |

# 1. INTRODUCTION

## A. Overview

The aim of this report is to provide basic information and to state fundamental concepts needed to implement the use of a multileaf collimator (MLC) in the conventional clinical setting. MLCs are available from all the major therapy accelerator manufacturers. The use of MLCs to replace conventional field-shaping techniques is not in itself expected to improve the local control of malignancy. The rationale for using MLCs in conventional radiation oncology is to improve the efficiency of treatment delivery. Thus, the intent of this report is to assist medical physicists, dosimetrists, and radiation oncologists with the acquisition, testing, commissioning, daily use, and quality assurance (QA) of MLCs in order to realize increased efficiency of utilization of therapy facilities. It is not the intent of this report to describe research into advanced applications of MLCs in conformal therapy or dynamic treatments.

A major limitation to the efficacy of radiotherapy treatment is the production of undesirable complications by the irradiation of healthy tissue inherent in a given radiotherapy technique. Many organs are relatively sensitive to radiation damage (the spinal cord, salivary glands, lungs, and the eyes are common examples) and must be given special consideration during radiotherapy treatment planning. In general, treatment planners attempt to optimize the dose distributions achievable with a given treatment strategy to deliver a tumorcidal dose of radiation to a target volume while minimizing the amount of radiation absorbed in healthy tissue. Explicit field shaping of the beam is required to reduce the amount of healthy tissue irradiated, and multiple beams are used to lower the dose absorbed by tissue outside the target volume. Conventional treatment strategies use a limited number of shaped beams and restrict the orientation of the beams to coplanar fields.

A conventional treatment machine shapes x-ray fields by a set of dense metal collimators (the term "jaws" will be used here) built into the machine. These collimators are positioned by the therapist using hand controls in the treatment room, and usually remain stationary during treatment. The collimator jaws of treatment machines produce rectangular beams. Conventional beam shaping is accomplished through the use of a combination of these collimator jaws and secondary custom beam blocks attached to the accelerator beyond the collimator jaws. Conventional blocks consist of either a set of lead blocks having a range of shapes and sizes that are placed by hand at each treatment session or cerrobend blocks fabricated individually for a given field applied to a specific patient (Powers et al. 1973). The beam passes through these lead-alloy shields which block portions of the rectangular radiation field outside the target volume. The beam blocks are fabricated based on the patient's treatment plan, using radiographic plane films or CT-scan data. A single patient may have as many as 10 radiation fields used during treatment, each with a different shape and requiring a unique beam block.

Beam blocks have several inherent disadvantages. The use of low-melting temperature blocks is time-consuming (one or two days are required to produce a set of blocks) and involves the handling of Wood's metal (cerrobend), a toxic material. Cerrobend (the most commonly used material) must be molten during block fabrication and can expose hospital workers involved in the fabrication process to toxic fumes if the vaporization temperature is accidentally exceeded. The process of block construction may also create toxic fumes from the melting of Styrofoam™. In the clinic the beam blocks, mounted on trays, must be attached and removed from the accelerator by the radiation therapist. Blocking trays can weigh over 25 pounds, and accidents involving dropped or falling blocks have injured therapists and patients. The therapists are also at risk to strains from lifting the blocks while standing in awkward positions (Glasgow 1980).

Newer accelerators allow more control over how the collimators are positioned; some machines can even produce wedge-modulated fields (normally produced with physical metal wedges) by moving a single collimator during treatment. Using computer control, it is now possible to control the jaws from commands sent to the collimators from the control console without entering the treatment room. The jaw positions for a particular field for a particular patient can be retrieved from a computer file.

One application of this increased capability is replacement of beam blocks for field shaping with the MLC. The MLC has movable leaves, or shields, which can block some fraction of the radiation beam; typical MLCs have 20 to 80 leaves, arranged in pairs. By using the computer controls to position a large number of narrow, closely abutting leaves, an arbitrarily shaped field can be generated. By setting the leaves to a fixed shape, the fields can be shaped to conform to the tumor. Given adequate reliability of the hardware and software, the use of MLC field shaping is likely to save time and to incur a lower operating cost when compared to the use of beam blocks; fabrication facilities and expenses will be reduced. Patient setup time during treatment may also decrease, allowing greater patient throughput. Adjustment in the field shape can be made quickly and conveniently by modifying the computer file containing the leaf-settings rather than having to recast a new cerrobend block. These factors are becoming more important in today's health care industry. However, in order to replace cerrobend blocks for fields that have a complex outline, more than one setting of the leaves is required, leading to the need for a more sophisticated control system and expanded dosimetry calculations.

There are three basic applications of the MLC. The first application is to replace conventional blocking. The field-shaping functions served by these familiar and widely used procedures can be largely duplicated by leaf position sets stored on a computer file to form a desired field shape. The files can be created especially for a given field to be applied to a specific patient in analogy to the fabrication of cerrobend blocks.

A second function of the MLC is an extension of the first. One variant of conformal therapy entails continuously adjusting the field shape to match the beam's-eye view (BEV) projection of a planning target volume (PTV) during an arc rotation of the x-ray beam (Takahashi 1965). This requires a large number of field shapes that are applied as a function of gantry angle during the arc. To implement this variant, one must change the positions of the leaves while the beam is being delivered. Such a capability makes feasible the third basic application of the MLC.

The third application is the use of the MLC to achieve beam-intensity modulation. Variants of conformal therapy have been considered that require each field be compensated or modulated. Various approaches to this modulation have been developed that use the motion of the MLC leaves during irradiation to create a dynamic compensating filter either for a number of fixed gantry exposures or for a continuously arcing fan beam and for a continuously arcing cone beam. These latter two applications of the MLC are advanced forms of conformal therapy and will not be considered in detail in this report.

## B. Summary of Configurations

In what follows, we shall adopt the following usage to describe the leaves (see Figure 1). The *width* of a leaf will be the small dimension of the leaf perpendicular to the direction of propagation of the x-ray beam and perpendicular to the direction of motion of the leaf. The *length* of the leaf shall refer to the leaf dimension

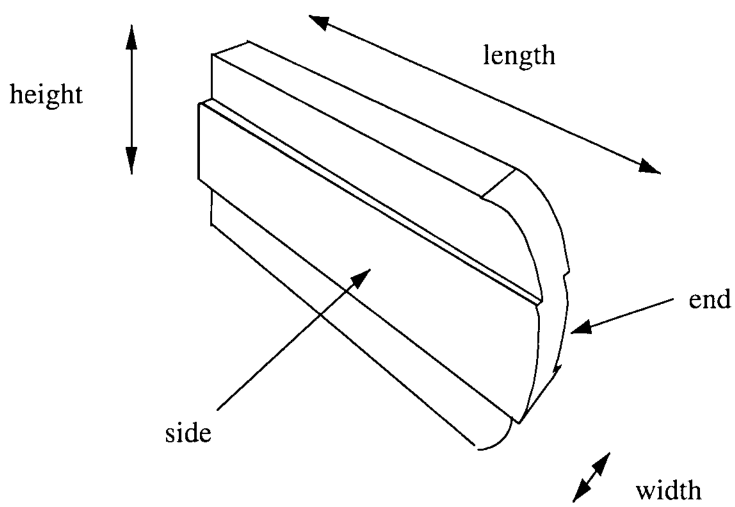


**Figure 1.** Schematic of generic MLC leaf illustrating leaf terminology. An example of a curved end and a stepped side.

parallel to the direction of leaf motion. The surface of the leaf inserted into the field along this dimension is the *leaf end*. The surfaces in contact with adjacent leaves are the *leaf sides*. The *height* of the leaf shall refer to the dimension of the leaf along the direction of propagation of the primary x-ray beam. The *leaf height* extends from the top of the leaf near the x-ray source to the bottom of the leaf nearest the isocenter. The height of the leaf determines its attenuation properties. The reduction of dose through the full height of the leaf will be referred to as the *leaf transmission*. The reduction of dose measured along a line passing between leaf sides will be referred to as *interleaf transmission*, and the reduction of dose measured along a ray passing between the ends of opposed leaves in their most closed position will be referred to as the *leaf end transmission*.

MLC configurations may be categorized as to whether they are total or partial replacements of the upper jaws, the lower jaws, or else are tertiary collimation configurations (see Figure 2). The particular configuration along with other collimator design aspects, such as whether the wedge is internal or external, creates a number of x-ray beam collimation and control configurations. MLC machines

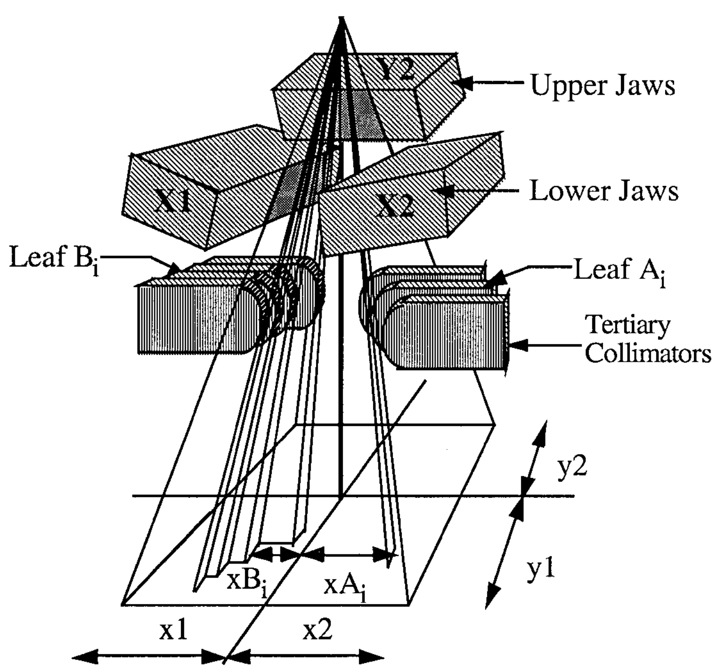


**Figure 2.** Generic schematic of a photon collimation system with upper and lower jaws and a tertiary multileaf collimator. The Y1 jaw has been omitted for clarity. The field dimensions in the plane at isocenter are indicated.

may place the tertiary block trays and the gantry housing closer to the patient than non-MLC machines. In some cases, wedges and compensating filter assemblies are also placed undesirably close to the patient. This limits the extent of some non-coplanar treatment techniques.

### *a) Upper Jaw Replacement*

This configuration entails splitting the upper jaw into a set of leaves. Currently the Elekta (formerly Philips) MLC is designed in this manner (see Figure 3). In the Philips design, the MLC leaves move in the y-direction (parallel to the axis of rotation of the gantry). A "back-up" collimator located beneath the leaves and above the lower jaws augments the attenuation provided by the individual leaves. The back-up diaphragm is essentially a thin upper jaw that can be set to follow the leaves if they are being ganged together to form a straight edge or else set to the position of the outermost leaf if the leaves are forming a shape. The primary advantage of the upper jaw replacement configuration is that the range of motion of the leaves required to traverse the collimated field width is smaller, allowing for a shorter leaf length and therefore a more compact treatment head diameter. The disadvantage of having the MLC leaves so far from the accelerator isocenter is that the leaf width must be somewhat smaller and the tolerances on the dimensions of the leaves as well as the leaf travel must be tighter than for other configurations.

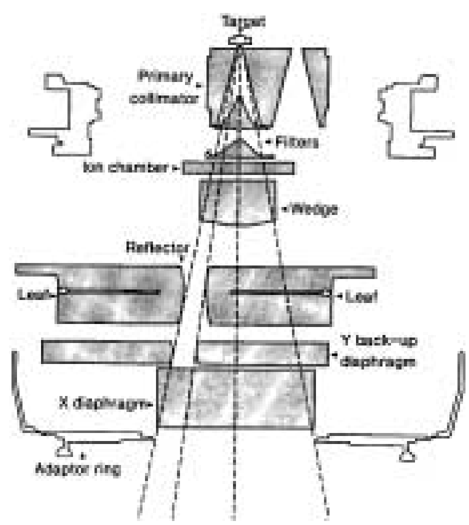


**Figure 3.** Schematic diagram of the Philips MLC. The upper jaw is replaced by the MLC leaves and a back-up diaphragm placed beneath the leaves follows the leaves to provide additional attenuation.

## b) Lower Jaw Replacement

The lower jaws can be split into a set of leaves as well. The Scanditronix Racetrack Microtron, as well as the Siemens and the General Electric (GE) MLC options use this configuration (see Figure 4). The GE MLC system is no longer being sold. In both the Scanditronix design and the Siemens design, the leaf ends are straight and are focused on the x-ray source. The Siemens design uses 29 opposed leaf pairs. The outer leaves of each leaf bank project to a thickness of 6.5 cm at the isocenter plane. The inner 27 leaf pairs project to a dimension of 1.0 cm at the plane at isocenter. All leaves can travel from the full open position (projecting to a field half-width of 20 cm) to 10 cm across the central axis. All the leaves are independently controlled and travel with a speed of up to 1.5 cm/sec. The leaves may be manually positioned with an MLC hand control and these leaf-settings can be uploaded to an information management Record and Verify (R&V) system. The leaf ends as well as the leaf sides match the beam divergence, making the configuration double-focused. The GE configuration uses curved leaf ends and contains a secondary "trimmer" similar to the Elekta back-up diaphragm. However, this trimmer is located above the upper jaws in the GE design (see Figure 4).

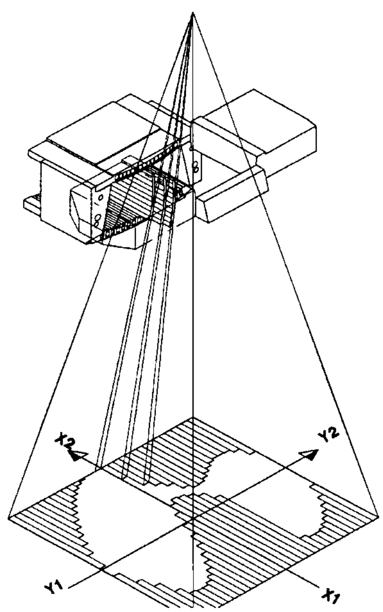


**Figure 4.** Schematic of the General Electric Medical Systems MLC that replaces the lower jaws. The leaves project to a width of 1.25 cm at isocenter so that 32 leaves are used to cover the 40-cm width of the field. A trimmer above the upper jaws is used to refine the penumbra at the leaf ends.

### *c) Third Level Configurations*

The Varian MLC is an example of a tertiary collimator system (see Figure 2). This device is positioned just below the level of the standard upper and lower adjustable jaws. This design was chosen to avoid lengthy downtime in the event of a system malfunction. Using this approach, it is possible to move leaves manually out of the field should a failure occur. Treatment can continue after replacement cerrobend blocks have been fashioned. The major disadvantage of placing the MLC below the standard jaw system is the added bulk. Clearance to the mechanical isocenter is an additional, but minor, problem. Clearance for the Varian MLC depends on the exact combination of beam modifiers used for a particular treatment situation. When the MLC is fitted and a block support tray is added for additional field shaping, clearance to the isocenter is the same as the non-MLC treatment head. Physical wedges are added below the blocks, and decrease clearance to some degree. Using the MLC without supplemental alloy blocks allows removal of the entire block support system and increases clearance. In this case, physical wedges are mounted on the face of the treatment head and clearance is usually acceptable. Of course, there is no change in clearance when the dynamic wedge feature is used. In addition to the question of clearance, the diameter of the head at the level of the secondary and tertiary collimator system is increased. Moving the MLC farther from the x-ray target requires an increase in the size of the leaves and a longer travel distance to move from one side of the field to the other. The end result is that a tertiary system decreases the collision free zone. For example, if a blocking tray holder is retained, patients whose treatment positions call for their elbows to extend laterally, such as in treatment of breast cancer, may not clear unless the blocking tray holder is removed.

### *d) Field-Shaping Limitations*

The field-shape limitations of the various collimators are shown in Figure 5. The top panel illustrates the field-shaping limits for the Siemens and Elekta (Philips) collimators. A representation of the Siemens leaf extension is shown at the top of the panel. Starting with the jaws and all the leaves positioned to define a 40-cm $\times$ 40-cm field, the four leaves at the top of this diagram have been moved into the maximum square field opening. The leaf at the top of the field is inserted to its maximum extension. It is extended 20 cm to the center of the field and an additional 10 cm across the centerline. This gives a maximum leaf travel for this collimator system of 30 cm. This is similar to the General Electric Medical Systems collimator illustrated in the top portion of the bottom panel in Figure 5.

The movement of the Elekta (Philips) collimator leaves is shown in the lower portion of the top panel of Figure 5. In this case, the leaves can extend 12.5 cm across the field centerline. The total travel distance for this system is 32.5 cm.

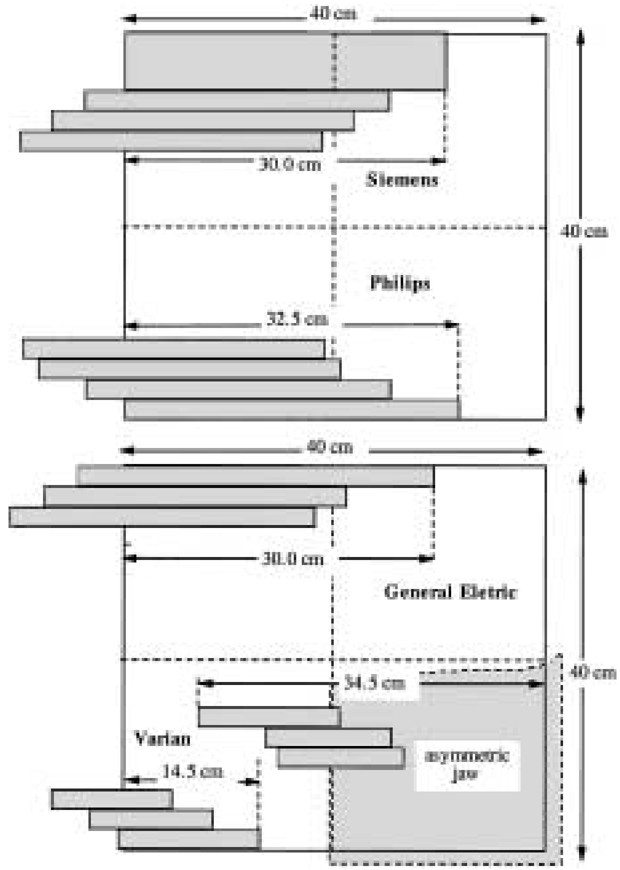


**Figure 5.** A comparison of the leaf travel configurations of commercially available MLCs. The maximum leaf extensions are compared to a 40-cm × 40-cm maximum field size.

The Varian collimator uses a different design. The leaves in the Varian collimator travel on a carriage to extend their movement across the field. However, the distance between the most extended leaf and the most retracted leaf on the same side can only be 14.5 cm. This means that it is not possible to obtain extensions similar to those shown in the other portions of Figure 5. The possible extensions of the Varian collimator are illustrated in the bottom portion of the bottom panel. Extending the leaves out to the field center is not possible when large fields are used. This limitation is most severe for large field widths. This can be illustrated by a medium field size of 20-cm width that is symmetric relative to the field center. In this case, the entire carriage can be moved so that the leaves can extend 4.5 cm (the 14.5-cm limit minus the 10-cm half field width) over the field center. For a similar field, the leaves of the other systems could be extended entirely across the width of the 20-cm field. However, when an asymmetric jaw is used to block half of the field (shown in the right side of the bottom of the bottom panel), the Varian carriage can be moved to the field center and a leaf can be extended 14.5 cm beyond the field center, further than any of the other systems. For single field block replacement, the Varian tertiary configuration is more limited than the other systems. On the other hand, this configuration lends itself to broader applications of intensity modulation.

Another potential limitation is the ability of leaves on one side of a field to interdigitate with neighboring leaves on the opposing leaf bank. In this case, the ends of odd-numbered leaves from the right-hand bank are driven past the ends of even-numbered leaves from the left-hand bank. The Varian collimator is the only system that can perform this maneuver. While this may not be important for most block replacement applications, potentially it can be used to create island blocks by using two exposures of the same field. Interdigitation also simplifies implementations of intensity modulation. For example, if superimposed beam segments at a fixed gantry angle are used for intensity modulation, unusual beam shapes that employ leaf interdigitation can improve the efficiency of dose delivery (Galvin, Chen, and Smith 1993). In general, interdigitation reduces the total number of photons that are needed to complete dose delivery that will reduce the patient dose due to leakage radiation.

## C. Attenuation

The leaves of the MLC must provide an acceptable degree of attenuation, must be shaped optimally to provide field shaping when working together throughout a range of field sizes, and must be integrated with the rest of the collimation system. Selecting the materials and designing the leaf shapes and positioning apparatus to achieve these ends is an engineering challenge.

### *a) Materials and Properties*

Tungsten alloy is the material of choice for leaf construction because it has one of the highest densities of any metal. Tungsten alloys are also hard, readily machinable, and reasonably inexpensive. An additional advantage is that they have low coefficients of expansion, so that parts can be machined to exacting tolerances, an important consideration with regard to interleaf separations. Pure tungsten has a density of 19.3 g/cm$^3$, but the alloys have densities that range from 17.0 to 18.5 g/cm$^3$, with varying admixtures of nickel, iron, and copper to improve machinability. Pure tungsten is very brittle and the machinability of tungsten alloy improves with decreasing tungsten content. Table 1 gives some typical properties of tungsten alloy for various densities.

**Table 1.** Properties of Tungsten Alloys

| | | | | |
|---|---|---|---|---|
| Density (g/cm$^3$) | 17.0 | 17.5 | 18.0 | 18.5 |
| Tungsten content | 90.5% | 93.0% | 95.0% | 97.0% |
| Nickel content* | 06.5 (7.0)% | 05.0 (4.2)% | 03.4% | 01.6% |
| Iron content* | 03.0 (0.0)% | 02.0 (0.3)% | 01.6% | 00.8% |
| Copper content* | 00.0 (2.5)% | 00.0 (2.5)% | 00.0% | 00.6% |
| $^{60}$Co HVL (mm) | 09.7 | 09.3 | 08.9 | 08.5 |
| Thermal expansion coefficient† | $6.1 \times 10^{-6}$ | | $5.5 \times 10^{-6}$ | $5.2 \times 10^{-6}$ |

*These are values from one manufacturer but are fairly typical of other manufacturers whose values may differ by less than 0.5%. The figures in brackets indicate alternative alloys having the same density.

† These are values from one manufacturer and for one temperature range. For a larger temperature range, the values are higher. Other manufacturers quote values about half of those given in the table.

### *b) Transmission Requirements*

When the upper or lower jaws are replaced with leaves, the transmission requirements are the same as those of a set of collimating jaws. The requirements for the tertiary arrangement are somewhat different. When the adjustable photon jaws of the linac are used to set the overall size of the field, it is only necessary that the leaves of the tertiary MLC attenuate the primary beam to the same extent as customized blocks, i.e., <5% or between 4 and 5 HVL (half-value layer). However, since there is transmission between the leaves, the transmission through the leaves should be lower than this to ensure that the overall transmission meets this criterion. This criterion is met by a thickness of approximately 5 cm of tungsten alloy. If one wishes to reduce the transmission by, say, a further factor of 5 to 1%, this would require an additional thickness of approximately 2.5-cm. Thus, for the tertiary MLC one has to trade-off in-field attenuation against space between the collimator head and the couch.

## D. Interleaf Transmission

The cross-sectional shapes of the leaves are quite complex and present a challenge to the manufacturer. The two important factors which determine this shape are that the leaves (1) are focusing in the plane orthogonal to their travel and therefore have to incorporate divergence and (2) have to overlap their neighbors to minimize interleaf transmission. The first requirement dictates a truncated pie shape while the second modifies the sides of the leaves. The angle of this pie shape is quite small: for a 1-cm leaf resolution at isocenter, the thickness at the bottom of

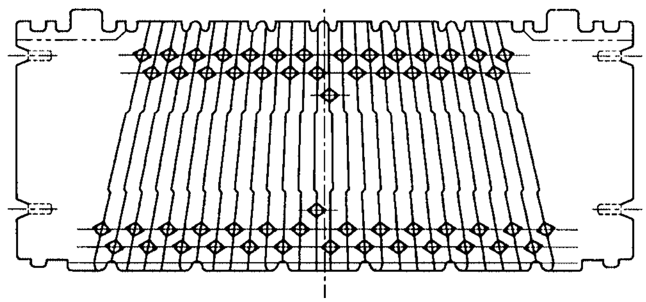

**Figure 6.** End view of the Siemens MLC showing the truncated pie shape of the leaves as well as the leaf side shape to reduce interleaf transmission.

the leaf is 0.5 mm greater than the thickness at the top of the leaf for a 5-cm leaf height (see Figure 6). The simplest way to overlap the leaves is to stagger the leaves midway along their height; but for mechanical integrity and ease of movement of one leaf relative to its neighbor, more complex arrangements have generally been found to be necessary. Most leaf designs have a profile that steps out and then steps back again. The GE leaf has a sinusoidal profile.

There are two situations to consider for interleaf transmission: (1) between the sides of adjacent leaves and (2) between the ends of the leaves. An idealized analysis of the fluence transmission at the leaf sides has been made (Jordan and Williams 1994). Figure 7 provides a schematic for discussion. This figure depicts leaves viewed end-on so that the fluence passing tangent to the sides can be analyzed. In Figure 7 the leaf side is simplified as a step function. A ray line along track a in Figure 7 passes through the entire height of the leaf and undergoes full attenuation. A ray passing along b is attenuated by about one-half of the leaf thickness. The ray line along c passes through the side offset of both neighboring leaves and undergoes nearly full attenuation. The resulting idealized interleaf fluence profile is indicated at the bottom of Figure 7. In practice, the theoretical valley in the center of the leakage profile is never detected. Although the overall pitch of the leaf pattern may be 1 cm, the profile of a strip irradiated by the retraction of a single leaf is somewhat wider (W′ in Figure 7), and has a penumbra broadened by the leaf side design, being governed by (W′ – W)/2. In practice, the depths of the leaf side steps are only fractions of a millimeter, and so the broadening is quite small.

Jordan and Williams (1994) used a Farmer-type ionization chamber and film to investigate the transmission properties of a Philips MLC system at 6 and 20 MV. Because of the different construction of this device, the results have to be interpreted somewhat carefully. In their investigation, they also examined the transmission for different gantry angles to assess the effect of gravity. Their results showed a maximum transmission of 4.1% at 6 MV and 4.3% at 20 MV between the leaves and 1.8% at 6 MV and 2% at 20 MV averaged over the leaves. The transmission

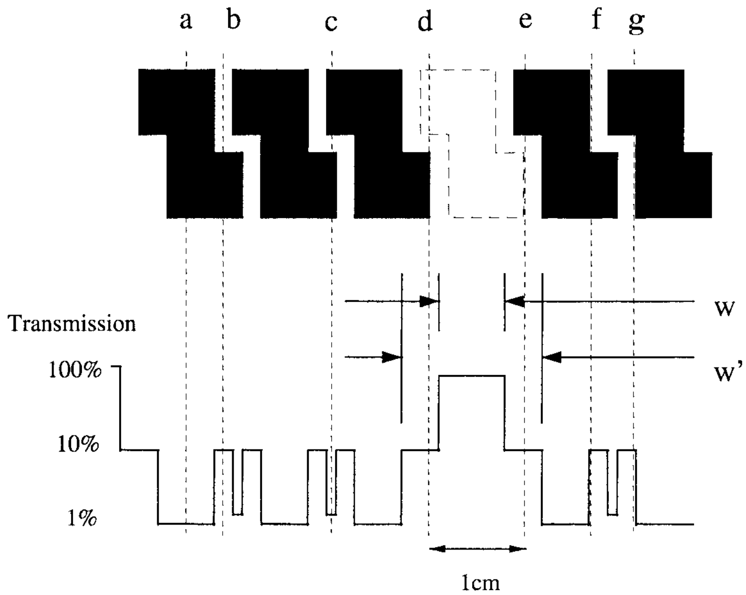


**Figure 7.** Illustration of different leakage paths between leaves and the effect of leaf cross-section shape on penumbra along the side of an MLC leaf.

through the ends of abutting leaves was found to be 51% at 6 MV and 61% at 20 MV. Of interest is that the transmission through the back-up jaws was about 11% vs. 0.5% for the standard x-direction collimators.

Measurements have been made (Galvin, Smith, and Lally 1993; Klein et al. 1995) of the transmission properties of a Varian MLC for 6-MV (1.5%–2.0%), 15-MV (2%) and 18-MV (1.5%–2.5%) x-rays using radiochromic film. Transmission between the leaves added an additional 0.25% to 0.75%. In addition, the screws that attach the leaves to the runners increased the transmission still further to a maximum of about 3%. These numbers were valid for both x-ray energies. These values are lower than those found for cerrobend alloy blocks (3.5%) and higher than those found for jaw transmission (<1.0%). Transmission through abutted (closed) leaf pairs was as high as 28% for 18-MV photons on central axis. Off axis the abutment transmission decreased as a function of off-axis distance to as low as 12%.

## E. Leaf End Shape

Adjustable secondary collimator systems have for some time been designed to follow the beam divergence as the field opens and closes. Collimators of this type are referred to as “focused.” Various approaches have been used to keep the face of each collimator aligned parallel to the primary fluence for all field sizes.

Most commonly, the collimator moves along the circumference of a circle that is centered at the x-ray target of the linac such that the end of the collimator is always tangent to the radius of the circle. Alternatively, the movement of the collimators can be restricted to a single plane perpendicular to the beam central axis, and a small independent portion of the front face of each jaw tilted as the position of the collimator changes so that agreement with beam divergence is maintained. This is the approach used on the current generation of Siemens accelerators. Either design is fairly easily implemented when only four individual jaws are involved. However, they are hard to apply to the significantly more complex situation where a large number of individual collimator leaves are moved independently. For this reason, at least two of the early commercially available MLC systems (Philips and Varian) have used a simpler approach. This design restricts the movement of the leaves to a single plane, and relies on shaping of the leaf face to produce an acceptable penumbra. The idea of shaping a collimator or leaf end to control penumbra width is more than 10 years old (Maleki and Kijewski 1983). This design is most easily visualized as a rounded end that is part of a circle (see Figure 8). There are two concerns over collimation with nonfocused leaf ends. First, the penumbra width can be larger than the penumbra generated by a focused or divergent edge. Second, the penumbra width might change as a function of the distance of the leaf end from the field midline. Attenuation of the edge of the field occurs in the rounded end along chords of the circle. These chords rotate around the end of the leaf as the leaf is moved through its range of travel. Since the chords all have approximately the same length, the attenuation just outside the field is always the

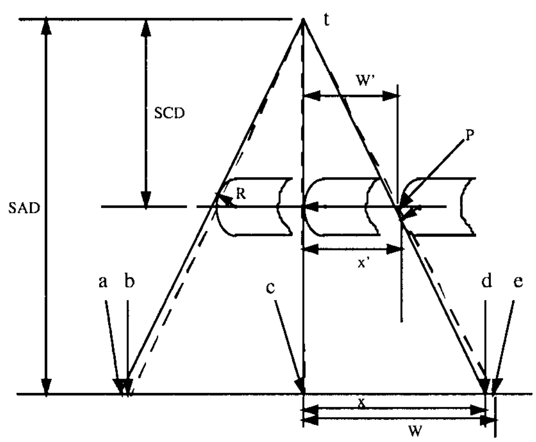


**Figure 8.** Schematic of ray lines that determine the form of the edge of the radiation field and light field at the curved end of an MLC leaf. SAD is the distance from the source to isocenter and SCD is the distance from the source to the center of the leaf. R is the radius of curvature of the leaf end.

same, and the penumbra is of the same width, although in principle it is somewhat greater than for a focused leaf. Different philosophies have been used to determine the radius of curvature for the leaf end, and flat sections have been added by some manufacturers (Galvin et al. 1992). There is also a question associated with the curved leaf end as to how to match the edge of the light field with the 50% dose border at the edge of the field.

Measurements on the Philips and Varian configurations have shown that these designs result in little change in the penumbra width as a function of leaf position, and that the penumbra at any position is within 1–3 mm of that obtained with a focused system or for alloy blocks with divergent sides (Galvin et al. 1992; Boyer et al. 1992; Galvin, Smith, and Lally 1993; Jordan and Williams 1994; Huq et al. 1995).

## F. MLC Control Features

MLCs produced by different manufacturers employ different mechanisms for moving the leaves accurately to their prescribed positions. The task of moving a leaf to the correct position normally involves the following procedures: (1) the detection of the position of leaf; (2) the leaf control logic; and (3) the mechanism that moves the leaf to position. Position sensors mechanically linked to collimators include video-optical systems, and linear encoders. For two-dimensional (2-D) field shaping, the controlling decision may involve dosimetry compensation, leaf speed settings, etc. The mechanisms that are used to drive the leaves include digital and analog motors driving individual leaves.

## G. Leaf Position Detection

Leaf positions must be detected in real-time to achieve safe and reliable position control. Depending on the type of multileaf system, the complexity and mechanism of leaf position detection varies. The following describes the mechanisms commonly used in existing commercial systems.

### *a) Limit Switches*

Limit switches are used in bi-state MLCs such as that developed by NOMOS, Inc. The open or closed state can be detected depending on which switch is turned on by the leaf.

### *b) Linear Encoders*

There are many types of linear encoders. The ones that are commonly used in MLC systems are high precision potentiometers. The linear range of detection and the accuracy are often in conflict. Such conflict can be resolved by using two potentiometers with correlated readings. The advantages of using linear encoders include simple read-out, less susceptibility to radiation damage, and good linearity and accuracy. The drawbacks are more wiring in the head structure, and more occupied space in the head. Since defective potentiometers are sometimes hard to detect, redundant ones are often required to ensure correct measurements.

### *c) Video-Optical*

Figure 9 illustrates a video-optical system for leaf position detection. The system uses the same light source for patient positioning as the light source for leaf position recognition. A retro-reflector is mounted near the end of each leaf. The light projected onto the leaf end is reflected back along the same path as the incident light. A beam splitter and mirror system channels the reflected light to a solid-state camera. An image is formed that shows the positions of the reflectors. By using an open aperture to create a narrow depth of field and focusing on the plane of the leaf tops, the image can be tuned such that only the reflectors are shown in the image acquired by the camera. The video signal is digitized and processed with an image processor in the MLC controller. Since all reflectors have the same shape and size, a simple feature recognition technique can be used to derive the positions for all the reflectors.

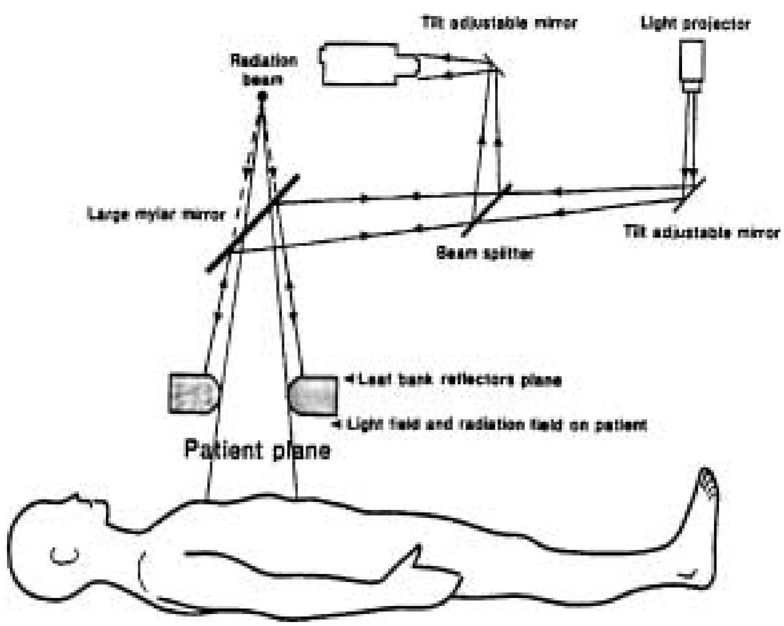


**Figure 9.** Illustration of a video-optical method of determining leaf position.

The advantages of the video-optical system include real-time display of the leaf positions, less wiring, and high spatial resolution. When using solid-state devices such as charge-coupled device (CCD) cameras, the system also provides high position linearity. However, most CCDs are not radiation resistant. Frequent camera replacements are therefore required.

### *d) Leaf Position and Control*

One issue that must be addressed in the implementation of a collimation system is the definition and control of collimator position. In Figure 2, these parameters are x1, x2, y1, and y2 for asymmetric jaws, and $xA_i$ and $xB_i$ for the ith opposing leaf pair. When the leaf ends are curved, the position of the field edge, defined as the position of 50% dose level in dose profile through the penumbra region, is determined by the collective effects of scattering and the leaf-end attenuation. Finding a zero reference for the positioning parameters of a flat-ended, focused collimator is relatively simple. In this case, the collimator is aligned with a ray line extending from the center of the x-ray target to the center of the field. This line will correspond approximately to the 50% point of a dose profile measured across the boundary of the field. That is, the fluence measured at a fixed distance from the x-ray source along a line running perpendicular to the projection of the collimator face will closely approximate a step function that drops from full value within the radiation field to zero at the geometric projection of the collimator edge. Thus, positioning the front face at the field center defines the zero reference, and a zero field size has opposing collimators closed and touching at this point. Finding a zero reference for an MLC with shaped leaf ends is more difficult. This is because bringing the leading point of a leaf with a curved end into alignment with the field centerline does not correspond to bringing the 50% fluence line to this position.

Figure 8 shows a schematic diagram of an MLC leaf with a rounded end placed at three positions. The distance from the x-ray source to the center of the leaf depth is given as SCD. The tip of the curve on the leaf end is at the leaf depth centerline at P. The distance to isocenter is given as SAD. The leaf end is shown with a radius of curvature R. The leaf is shown in three positions; collimating to the outside of the axis of rotation of the collimator such that P projects to e; collimating to the axis of rotation of the collimator such that P projects to c; and collimating across the axis of rotation of the collimator such that P projects to b. If P is moved from position c to position e, it moves a linear distance $W'$ along the line a distance SCD from the x-ray source, whereas its projection moves a distance $W$ at the isocenter distance, SAD. Were the leaf position to be taken to be related to the distance of leaf movement $W'$, it would be calculated using the following relation

$$W = W' \cdot \frac{SAD}{SCD} \tag{1}$$

This equation does not describe the position of the field edge because it uses the tip of the curved leaf end, point P, as a reference. It has been shown (Galvin, Smith, and Lally 1993) that the light field width will be up to 5 mm smaller than this geometric dimension when curved leaves define the edge and Equation (1) calculates the leaf position. This difference is illustrated by points a and d in Figure 8. An alternative is to use the ray line running from the center of the x-ray target tangent to the curved leaf face for all leaf positions in the field. These are the ray lines ending at a, c, and d in Figure 8, resulting in a field half-width formed by the dimension *x*. There is a nonlinear difference between the light field projection *x* and the linear leaf displacement $W'$. This light field position *x* is approximately

$$x = W - \Delta \tag{2}$$

$$x = \frac{W \cdot SCD \pm R \cdot SAD \cdot \left(1 - \dfrac{SAD}{\sqrt{SAD^2 + W^2}}\right)}{SCD \pm R \dfrac{W}{\sqrt{SAD^2 + W^2}}} \tag{3}$$

The relationship is nonlinear with respect to the physical motion of the leaf. Using this relationship reduces the size of the deviations between the selected leaf position and the light field projection of any leaf to a maximum of about 1 mm. This nonlinear relationship is currently accounted for by the leaf position parameters of the Varian MLC. However, it does not give exact agreement between the radiation field and the light field. The x-ray fluence falls to 50% (relative to the value just inside the open portion of the field) along a ray line through a chord of the arc of the rounded leaf end that is equal to 1 HVL. In Figure 8, the ray ending at e is close to such a line. Thus the x-ray field is wider than the light field by a small nearly constant value. Calculation of the projection of the 1 HVL chord position puts it less than 1 mm outside the light field.

In the Philips MLC design, the discrepancy between the light field and the radiation field is reduced by shortening the distance between the light source and the collimator by approximately 1 cm. As a result, the shadows of the conventional collimators that define the light field in the dimension perpendicular to the leaf motion will always be greater than the corresponding radiation field size. This is corrected by mounting "light trimmers," a pair of thin aluminum blades at the edge of the jaws, to trim the light field down while maintaining the radiation field size. Theoretically, this treatment produces accurate field size matching only at one distance (normally 100 cm) from the source. It can be shown analytically that the error introduced by this treatment at other distances in the practical patient setup range is minimal.

In the Philips and Varian MLC designs, the relation of field edge position (50% attenuation) and the leaf travel is stored in the MLC controller as a look-up table. The amount of leaf travel needed to move a leaf to its prescribed position is interpreted from the measured relationship. The speed of the leaf is also controlled to move the leaf to position as fast as possible with considerations of smoothness and safety. The main safety concern is collision between opposing leaves.

### *e) Driving Mechanism*

For MLCs capable of 2-D field shaping, motors are used to move the leaves. Linear screw bars are normally used to translate rotations to linear motion. The speed of the leaf travel varies between 0.2 mm/sec to as high as 50 mm/sec, depending on the design. In most cases, the leaves move at a speed of 1–2 cm/sec.

### *f) Calibration of MLC Leaf Positions*

An important procedure to ensure accurate leaf positioning is the calibration of leaf positions. Through the calibration, the measured signals, such as voltages from the potentiometers or pixel numbers from a solid-state camera, and the actual leaf positions establish a one-to-one relationship. Periodic checking and recalibration are also needed to ensure the integrity of the controlling system.

The Varian MLC calibrates the leaf positions using narrow infrared beams built into the collimator assembly that transect the paths of the leaves. The calibration procedure is carried out automatically each time the MLC operating system is initialized. Each leaf is driven through its range of travel. As a given leaf intersects the infrared beam, the values returned by its position encoders are acquired. These values are used along with equation (3) to calibrate the leaf position. The calibration values are saved in a table for use by the control system.

In the Philips MLC system, which uses a video optical controlling mechanism, four reference reflectors are fixed on the head structure. The positions of the four reflectors establish a fixed frame of reference, which requires film exposures of regular fields with different field sizes set by a set of default calibration values. The actual field sizes measured from the films set the final calibration. During operation, the positions of the four reference reflectors are acquired and checked every 0.1 sec.

### *g) The Control of Back-up Jaws*

In some MLCs, the back-up jaws are designed as part of the MLC system and are controlled by the MLC controller. In other systems, the jaws are controlled separately by the linear accelerator controller. When components of the upper or lower jaws are required to achieve acceptable leakage through the MLC portion of the collimation system, the jaws must be coordinated with the leaves to minimize the leaf transmission and interleaf leakage, and to achieve better penumbra.

Minimal leaf transmission and interleaf leakage is achieved by setting the jaws such that they at least circumscribe the irregular field formed by the leaves. For many clinical applications, it may be desired to use the jaw to provide a considerable portion of the field circumference. In these cases forcing the jaws to circumscribe the MLC outline is not desired. In the direction of leaf motion, the jaws can be positioned to sharpen the penumbra and partially compensate for affected curved leaf ends. In the direction perpendicular to that of leaf motion, the jaws should always shape a segment of the beam edge. In the Philips MLC system, this is achieved by withdrawing the leaf that contributes to the penumbra. As observed in Table 2, the variations in design are significant. It is interesting to note

**Table 2.** Summary of MLC Configurations for Various Treatment Machines

| **Source To** | **Varian CL2100C** | **Elekta (Philips) SL** | **Scandatronix Microtron** | **Siemens Digital Mevatron** | **General Electric Saturne 43*** |
|---|---|---|---|---|---|
| Bottom of upper jaw | 35.7 cm | 42.6 cm | 47.5 cm | 27.8 cm | 33.6 cm |
| Bottom of lower jaw | 44.4 cm | 50.9 cm | — | 35.9 cm | NA |
| Leaf bottom | 53.6 cm | 37.3 cm | 67.5 cm | — | 45.7 cm |
| Block tray | 65.4 cm | 67.2 cm | 70.6 cm | 56.0 cm | 61.0 cm |
| Compensating filter tray | 69.2 cm | N/A | N/A | N/A | 50.5 cm |
| Top of internal wedge | N/A | 18.6 cm | 22.0 cm (45°)<br>20.5 cm (15°) | N/A | 22.9 cm |
| Gantry housing | 57.9 cm | 52.9 cm | 71.0 cm | ****43.0 cm | 50.0 cm |
| Leaf thickness | **5.53 cm | 7.5 cm | 7.5 cm | 7.6 cm | 10.0 cm |
| Maximum height of blocks | 7.6 cm | 11.9 cm | — | 7.5 cm | 11.0 cm |
| Number of leaves | $26 \times 2$<br>$40 \times 2$ | $40 \times 2$ | $32 \times 2$ | $29 \times 2$ | $32 \times 2$ |
| Width of leaf at isocenter | 1.0 cm | 1.0 cm | 1.25 cm | 1.0 cm | 1.25 cm |
| Shapable field (cm × cm) | ***$40 \times 26$ cm$^2$<br>***$40 \times 40$ cm$^2$ | — | $31 \times 40$ cm$^2$ | — | $40 \times 40$ cm$^2$ |
| Leaf travel over isocenter | 16.0 cm | 12.5 cm | 5.0 cm | 10.0 cm | 10.0 cm |

*Sale of the GE accelerator has been discontinued since the production of this report.
**The Varian leaf is made of denser tungsten than the Philips leaf.
***Depending upon the field shape, the width may be limited to <40 cm.
****Accessory holder bolted in place.

that the machine with the leaves closest to the source (Elekta) has leaves with ends that are not double focused (curved ends), while the machine with the leaves closest to the patient (Scanditronix) has leaf ends that follow divergence. Parameters such as those stated for the particular machine are important for treatment planning, for both penumbra calculations, but more importantly, to account for potential collimator/wedge/tray and patient/table collisions. In the tertiary Varian system, it is necessary to ensure that a jaw covers the trailing edge of a leaf. This is the reason why the leaf span range of only 14.5 cm from the carriage set by the leaf length prohibits large irregular fields from being formed. For tertiary systems, the collimator jaws are used in concert with the leaves to shape the field. With the Varian system, where interleaf leakage is minimal, the X-jaws that move along the leaf direction can be placed close to the boundary, but can have settings that accommodate multiple field treatments. For example, opposed lateral fields, where the right lateral field would ideally have jaw settings of X1 = 4.8 cm and X2 = 6.2 cm, the opposite would take place for the left lateral field. In this case, making all the X-settings 6.2 cm would be simple, and without consequence of increased interleaf transmission. On the other hand, the Y-jaws should be used to define the upper and lower borders, due to the finite step size imposed by the leaves.

## H. Summary of MLC Configurations

The MLC configurations generally available at the time of the preparation of this report are summarized in Table 2. Table 2 lists characteristics of five particular treatment machines with MLCs. The Varian C2100C has a third-level MLC configuration and also has the option of placing the wedges above or below the block tray. The Elekta (Philips) SL Asymmetric series has standard or short block tray options, and contains an internal wedge. The Scanditronix Microtron has internal wedges at different distances, and essentially no block tray.

## I. Nonconventional MLCs

For small fields such as those used for brain tumors or boost fields in the head and neck, finer resolution of the field margins may be required than for larger PTVs prescribed around gross tumor volumes for which wider margins are required because of inherent organ motion. Several miniature multileaf collimators (miniMLCs) have been developed to be used for these cases (Shiu et al. 1997). Irregularly shaped brain tumors present challenges for treatment using conventional radiosurgical techniques. Treatment of multiple isocenters by stereotactic teletherapy (or multiple isocenters used by linac radiosurgery) often results in high dose inhomogeneities, with which complications have been associated.

Dynamic field shaping that produces the prescribed dose conformal to the target volume is one strategy that may be used to reduce dose to normal brain tissue while minimizing the dose inhomogeneity within the target volume. A number of commercial firms have recently developed miniMLCs to the point that they can be placed on the market.

MiniMLCs have been typically configured as self-contained accessories that can be attached to the collimator of a linear accelerator for specific treatment techniques and removed for conventional use of the machine. Fiber-optic transmission lines are used to communicate with a PC-based digital control system. The photon jaws of the accelerator are set to a fixed field size during the use of the miniMLC so that the leaves of the miniMLC need be only long enough to cover a reduced maximum field size.

Another nonconventional MLC system is the MIMiC device provided by NOMOS Corporation (Carol 1992). This is a system intended to be inserted into the blocking tray of a linear accelerator. It is designed to collimate the x-ray field to a fan-beam that is dynamically modulated by short-stroke leaves as the gantry of the accelerator is rotated. The modulated fan beam irradiates a transverse plane of the patient that is 2 cm thick. The leaves are either fully inserted into the beam or fully retracted, providing either full attenuation or no attenuation at a given gantry angle.

## J. Computer System Configurations for MLC Leaf Prescription

For effective clinical application of MLCs to shaped radiation fields, field outlines must be translated into MLC leaf position tables. The intended leaf positions contained in these tables must then be communicated to the control computer that drives the MLC. There are at least three techniques utilized by manufacturers of MLCs and treatment planning systems for doing this: (1) a workstation employing a manual digitizer and a light box, (2) an off-line workstation employing a digitized image of a simulator film or digitally reconstructed radiograph (DRR), and (3) beam's-eye virtual simulators that function independently or as part of a treatment planning system. Computer workstations have been developed by the various vendors to acquire, store, and communicate the MLC prescription data. Prescription data includes the MLC leaf settings, any required jaw settings, and identification of the treatment field. In this discussion we will call these workstations multileaf collimator prescription preparation systems (MLCPPS). In addition to vendor-supplied workstations, systems have also been developed by MLC users (Du et al. 1994, LoSasso et al. 1993). The MLC prescription preparation system acquires the prescription images from different sources, such as film scanners, the simulator's fluoroscopic video signal, and radiation treatment planning systems. The multileaf collimator angle and leaf and jaw positions (such as values depicted

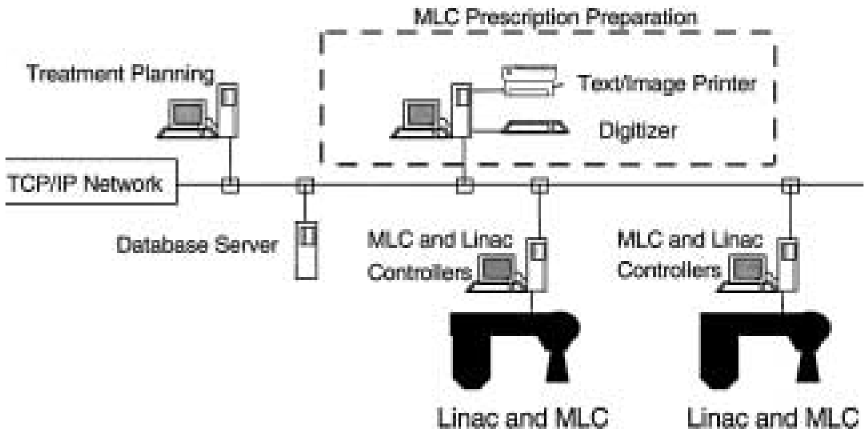


**Figure 10.** Schematic of MLC prescription preparation workstation and it relationship to other parts of the treatment planning and delivery system employing MLCs.

in Figure 2) are set from the desired field contour defined on the prescription images, by using different optimization criteria. Interactive graphical tools are normally included for manual adjustment of collimator angle and leaf positions. Data files of the final leaf positions are transferred to the multileaf collimator controller via a network link or using other media (see Figure 10). Once MLC field shapes can be developed through a network chain, multiple versions of an MLC field-shape file can be saved at different locations. The existence of multiple versions can be a significant quality assurance issue unless the system is carefully designed and implemented to avoid treating the patient using an older version that defines an undesired field shape. The software should be designed such that only one approved treatment file is saved on a treatment file server. If edits are made to the field shape, the treatment file should be changed only with password-protected security. The software should be available to edit the field shape, but provisions for revising the file that will be used clinically should be clearly indicated and a verification of the new shape required.

### *a) Manual Digitizer and Lightbox*

The leaf positions can be determined by digitizing a projected treatment portal using a digitizing tablet. A contour of the desired portal is drawn by hand using the digitizer. Software provided by the MLC manufacturer positions the leaves relative to the digitized portal using one of the algorithms described below. In general, digitizing tablets consist of a pointing device, a flat panel on which to place a film or other hard-copy portal graphic depiction, and hardware and electronics to determine the location of the pointing device. The flat panel is backlit to assist in the digitization of portals marked on radiographic film. Digitizing tablets use a variety of techniques to determine the position of the pointing device, such as the stereographic determination of the sound of a spark generated at the end of a pen-shaped pointing device. In each case, the location of the pointing device is determined by the measurement of a physical quantity that is related to the location of the pointer. This is accomplished by a calibration procedure dictated by the digitizing manufacturer and integrated into the software provided by the MLC manufacturer. The calibration procedure may involve the determination of the orientation and scale of fiducial points in the radiographic image (for example, the digitization of three points at a predetermined relative orientation). The system may then require that the radiographic film be placed in a precise orientation and location relative to the calibration points. Other calibration schemes may allow relatively arbitrary orientation and placement of the film. In these cases, the orientation and location of the isocenter and collimator axes will be identified.

### *b) Raster Film Digitizer*

Some MLCPPSs use raster digitized images. The field prescription can be acquired by digitizing the simulation film with such a film digitizer (Du et al. 1994). The image of the simulation film is displayed for the operator, and the field prescription may be traced out with a pointing device such as a mouse. The location and rotation of the treatment field axes, and the magnification of the digitized image are then established using fiducial points within the simulator film image. The advantage of this approach over the manual digitizer is that anatomic information is transferred to aid the operator in the process of setting and verifying the MLC leaf positions.

### *c) Virtual Simulation*

Finally, the MLC leaf positions may be defined using a virtual simulator. A virtual simulator consists of software and hardware that uses volumetric patient information (e.g., from a volumetric CT study) to conduct an off-line simulation of the patient. External radiation beams can be applied, with the generation of BEVs, DRRs, and, after contouring of target volumes, automatic portal definition. MLC control files may also be generated using the software.

### *d) Prescription Data Transfer*

The prescription data can be recorded in both soft and hard forms. The MLCPPS should provide data pathways between computers in the hospital and outside world (for example, treatment planning workstations) and the computers controlling the linear accelerators. The digitizing station will likely not be the same computer as used for treatment. Therefore, a strategy must be in place to transfer the MLC setting file from the digitizing station to the treatment computer. The collimator leaf coordinates can be downloaded to the MLC control unit via a network link, can be transferred using floppy disks, or can be printed out for manual entry at the MLC system. The simplest of these schemes is to use a floppy disk. The files are downloaded using either built-in transfer routines in the manufacturer's software, or by a file copy or move routine using DOS, Windows, or another operating system. The floppy is then physically inserted into the controlling computer and the file accessed or copied for routine clinical use.

However, the technology of choice to achieve this data flow is a local area network (LAN). In most cases, transferring the data through the network is the most convenient and reliable method. With the use of the MLCPPS, the average time to digitize the MLC fields can be reduced to about 10 minutes. Small modifications of the field shapes can be efficiently accomplished as well. For security reasons, the segment of the LAN that contains the accelerators should be protected from other segments of the LAN by the use of different communication protocols and a bridge or router. There is a wide variety of network hardware and software available to allow access of one computer's file system from another computer. The MLC file can either remain resident on the digitizing computer, be placed in an intermediate file server, or be transferred through the network to the controlling computer. The advantage of keeping the file on a file server is that only one copy of the file needs to be produced. However, normal clinical operation then relies on continuous network access. If the network fails, then either clinical treatments cease, or a temporary backup data transfer system must be employed (e.g., floppy disks). Copying the MLC files to the controlling computer may facilitate clinical operation during network problems, but they entail an additional step of copying the MLC files to the local hard drive and keeping track of the file copies.

This strategy can also be used if the MLC leaf setting computer is a commercial treatment planning system. Most modern systems make extensive use of local area networks for communication with peripheral and data acquisition devices (such as CT). Therefore, a LAN is ideally suited for MLC-file transfer if the files are generated using the treatment planning system. Three-dimensional (3-D) treatment planning computers are or will be capable of setting the MLC leaves and generating the appropriate control files for downloading to the MLC.

## 2. MONITOR UNIT CALCULATIONS

Monitor unit (MU) calculation requires both in-air and in-phantom scatter factors, which are commonly denoted as Sc and Sp, respectively. The use of an MLC for field shaping does not change the way the in-phantom scatter is calculated. The in-phantom scatter depends on the final field size projected on the patient.

Methods for calculating in-phantom scatter are well established and they will not be part of this report.

The main difference in MU calculation when an MLC is used for field shaping is in the determination of the in-air output ratio Sc, which is also referred to as the *collimator scatter factor,* the (*in-air*) *output factor,* and the *head scatter factor*. Traditionally, when radiation fields are shaped with collimator jaws and cerrobend blocks, two different equivalent field sizes are used for determining the in-air and in-phantom scatter factors. The effective square field size of the rectangular field shaped by the collimator jaws is used to determine the collimator scatter factor (usually from a look-up table) and the irregular field shaped by the cerrobend block is used for in-phantom scatter calculations. For irregular fields shaped with an MLC, an accurate method for MU calculations depends upon the MLC design, as explained in the following.

## A. The Physics of In-Air Photon Scatter

The change in in-air output with field size is a well-understood phenomenon. Although it is referred to as the collimator scatter factor, the major contribution is not from the motorized variable collimators but from other parts in the treatment head as pointed out by Patterson and Shragge (1981); Kase and Svensson (1986); Luxton and Astrahan (1988); Dunscombe and Nieminen (1992); Jaffray et al. (1993); Ahnesjo, Knoos, and Montelius (1992); Ahnesjo (1994,1995); McKenzie and Stevens (1993); Chaney, Cullip, and Gabriel (1994); Sharpe et al. (1995); and Zhu and Bjarngard (1995). Different models have also been proposed to predict the output factors (Dunscombe and Nieminen 1992; Ahnesjo, Knoos, and Montelius 1992; Sharpe et al. 1995; Lam et al. 1996). All these models consider the photons reaching the calculation point in air from both a focal point source and an extended extra-focal source. The extra-focal source is not a physical source but a virtual source modeled to include all the scatter photons in the photon beam coming from above the secondary collimator. The location of the extra-focal source can therefore be considered anywhere above the secondary collimator although most of the models consider it to be at the bottom of the flattening filter. Depending on the design of the accelerator head, backscatter from the collimators to the monitor chamber may also contribute to the output variations with collimator settings (Huang, Chu, and Bjarngard 1987; Luxton and Astrahan 1988; Kubo 1989; and Duzenli, McClean, and Field 1993). These studies provide the physical background for predicting the machine output variations with field size.

Based on these understandings, the collimator scatter factor at a calculation point is mainly determined by the area of the extended source as seen by this point through different levels of collimators. For linear accelerators equipped with conventional jaws, because the upper collimator jaws are closer to the source than the lower jaws, the same size of opening made by the upper and the lower jaws in the BEV are different when viewed from the point of calculation. A collimator setting that projects a square field into the BEV will project a rectangle when viewed from the point of calculation to a plane at the bottom of the flattening filter. As a result, a 4-cm × 8-cm field and a 8-cm × 4-cm field will, by definition, project as equal areas in the BEV projection, but will project into different areas in the flattening filter plane, and therefore will exhibit different in-air outputs. This is commonly known as the *collimator exchange effect*. For the same reason, the position of the MLC in the treatment head determines how the collimator scatter factors can be calculated accurately.

When an MLC is implemented as an upper or lower jaw replacement of a secondary collimator, the MLC affects the output factor much more strongly. The radiation field is defined jointly by both the MLC and the remaining set of jaws. The output factors must then be calculated using the irregular field shape instead of the rectangular field circumscribing it. Depending on which set of jaws the MLC is replacing, different methods should be used.

## B. MLC Replaces the Upper Jaws in the Secondary Collimator

If the MLC is located at the position of the upper jaws in the secondary collimator, as in the Philips MLC design, the irregular field shape determines both the collimator scatter and the phantom scatter. In the Philips design there is a pair of jaws of small height (also called backup diaphragms) situated under the MLC leaves and motorized to travel in the same direction as the leaves. These backup jaws serve to block the interleaf transmission outside the radiation field. They are normally set at the same position as the outermost leaves and make only a small contribution to the head scatter. The lower jaws, which move in a direction perpendicular to that of the leaf travel, define the beam aperture in that dimension and block the transmission from the gap between the ends of any opposing banks of leaves outside the radiation field. Although the lower jaws form part of the field boundary (in BEV), they generally do not restrict the view of the extended extrafocal source from the calculation point. This is because the leaves above the lower jaws are set at closed positions outside the radiation field. Therefore, the collimator scatter factor is determined mainly by the MLC shapes. There is little collimator exchange effect. If there is no additional tertiary blocking, the same MLC-formed field shape could be used for calculating both the collimator scatter factors and the in-phantom scatter factors. This implies that the equivalent square fields obtained from in-phantom irregular field calculations can be used to look up in-air output factors and vice versa, provided no other field shaping device is used. Palta, Yeung, and Frouhar (1996) measured the collimator factors of circular, diamond, and elliptical fields formed by the Philips MLC and concluded that the collimator scatter factor can be accurately described by calculating the equivalent square of the MLC-shaped field.

## C. MLC Replaces the Lower Jaws in the Secondary Collimator

If the MLC replaces the lower jaws in the secondary collimator, as in the MLC designs of Siemens and General Electric, both the MLC leaf positions and the upper jaw positions determine the collimator scatter factor. Since the jaws are closer to the effective collimator scatter source, they define the field aperture in the dimension perpendicular to the direction of leaf travel in both the BEV and in the projection of the calculation points. The in-air output factors show collimator exchange effect. Unlike the MLC design where the MLC replaces the upper jaws, different field shapes should be used for determining the in-air and in-phantom scatter parameters. The collimator scatter factor should be determined from the irregular fields viewed from the calculation point. Different methods can be used to calculate the collimator scatter factor as described in section E below.

## D. MLC as Tertiary Collimator

As with cerrobend blocks, when the MLC is used as a tertiary collimator along with the upper and the lower collimator, the collimating elements defined by the MLC is closer to the plane of any given calculation point than the upper or lower jaws. Unless the MLC-shaped field is substantially smaller than the rectangular field formed by the secondary collimator jaws, the tertiary blocking boundary will not affect the projection of the field size from the calculation point back to the effective scatter source. The jaw opening primarily determines the collimator scatter factor. The method of MU calculation is the same as the traditional method using cerrobend blocks. The in-phantom scattering parameters are calculated using the final field shape projected into the phantom.

The Varian MLC is a tertiary blocking configuration. The secondary collimators are unaffected by the installation of the MLC, and therefore provide the same scattered radiation fluence as a function of collimator setting as the same accelerator model without an installed MLC. Boyer et al. (1992) demonstrated that the effect of the MLC on central axis MU calculations is similar to that of a cerrobend block. Therefore, parameters used in monitor unit calculations that utilize the blocked field size will instead use the MLC-defined portal size, while parameters that are functions of the collimator setting are affected insignificantly by the presence of the MLC. For example, Boyer measured the dose rates of square fields blocked to 50% of the collimator-defined areas. The dose rates of these portals were compared against dose rates calculated using procedures defined for cerrobend blocking. The measurements were made at depths ranging from dmax to 20 cm.

For 6-MV and 18-MV beams, the measured dose rates were found to agree with calculation to within 1.7% and 2.5%, respectively. However, it is important to note that the machine output can deviate from the predicted when the area of the field shaped by the tertiary collimation is less than about 50% of the original field area. As the field area formed by the tertiary collimator decreases below 50% of the secondary collimator shaped field, the output factor falls below that predicted based on the settings of the secondary collimator jaws. This can be important when intensity modulated beams are delivered using dynamic multileaf collimation without the collimator jaws tracking the individual field segments.

## E. Methods for Calculating Collimator Scatter Factors of Irregular Fields

When the radiation field is shaped by collimator jaws, the collimator scatter factors for the rectangular fields are estimated by computing the equivalent squares using their area to perimeter ratio (Day and Aird 1983). The collimator scatter factor for a rectangular field is assumed to be the same as that of the equivalent square field, which can be interpolated from measured output factors of square fields. When the field shape formed by the secondary collimator is irregular, it is less clear what method for calculating the collimator scatter factor will produce an acceptably accurate value. Because the physical origin of collimator scatter remains unchanged when an MLC is used for radiation field shaping, many methods based on extrafocal radiation sources for calculating collimator scatter factors of rectangular fields can be used to estimate the collimator scatter factors of MLC-shaped irregular fields.

The methods which can be readily applied for calculating collimator scatter factor for MLC-shaped irregular fields are those based on convolution/superposition algorithms (Ahnesjo, Knoos, and Montelius 1992; Sharpe and Jaffray 1995). If the extended extrafocal source can be assumed to be radially symmetric, methods commonly used for in-phantom scatter calculations, such as the conventional Clarkson sector integration method (Clarkson 1941), can also be borrowed for calculating the in-air scatter. Collimator scatter factor can also be integrated radially or in both x- and y-dimensions if the derivatives dSc/dr (r is the radial distance from the central axis) or $\partial S_c/(\partial x \partial y)$ can be derived from measurements. For these integration methods to be valid, the field dimensions in both the measurements and the calculations should be projected from the calculation point back through the collimation system to the effective source plane. When sector integration is used, the collimator scatter factor for zero-field size has to be extrapolated from measured results similar to the derivation of scatter-air ratios. Collimator factor calculations for MLC-shaped fields are still an area of active research.

# 3. MLC ACCEPTANCE TESTING, COMMISSIONING, AND SAFETY ASSESSMENT

## A. Acceptance Testing

The MLC should function according to manufacturer specifications. Acceptance testing provides the opportunity for the user to become familiar with the MLC and to confirm that it does in fact meet the stated criteria for acceptance. These tests do not guarantee long-term accuracy and reliability. As with other equipment, frequent QA testing should be performed initially, and as confidence builds, the frequency may be relaxed to balance effort with anticipated need.

### *a) Mechanical Axes Alignment*

Since the mechanical axes of the accelerator form the basis to which most major systems (e.g., optical, radiation) are referenced, a thorough check of the mechanical axes alignments should be performed. These include gantry axis, collimator axis, and combined rotations with couch rotation, and jaw and leaf symmetry with the collimator axis. Except for the last check, these tests are those routinely performed during an accelerator installation. Special consideration is in order when the MLC is retrofitted to the accelerator. During accelerator installation, mechanical and radiation parameters are established such that the overall agreement of measured light and radiation field dimensions with the digital jaw position indication is within specifications. This may include adjustments to the machine head at the time of the accelerator installation without consideration of a subsequent MLC installation. Furthermore, the weight of the MLC adds a burden to the treatment head support structures. For these reasons, the overall alignment may be degraded with the addition of an MLC. The installation of an MLC on existing equipment should be accompanied by measurements sufficient to realign the original equipment, if necessary.

### *b) Optical Axes Alignment*

Typically, once the mechanical axes of the collimator and the gantry are aligned, the optical and radiation axes are checked. This may be carried out with a series of light and radiation coincidence tests that compare fields having collimator angels that differ by 180°, using the collimator projections as reference. This test will also detect flat collimator faces that are out of focus with the source. Collimator and gantry spoke shots are also useful and should be registered to the mechanical isocenter. Any misalignment is generally more serious for collimators which are closer to the source due to geometric magnification. Therefore, focused MLCs that replace the conventional jaws require the most careful alignments, while MLCs with rounded leaf faces which are located below the jaws are usually within tolerances met by the jaws. Accordingly, these parameters should be tested for the following situations: (1) jaws or backup diaphragms alone and (2) selected leaf ends and sides from selected locations within the leaf banks, across the full range of motion, at 0°, 90°, 180°, and 270° gantry angles.

### *(c) MLC Performance*

Appropriate tests should be conducted for the following parameters:

*Projected leaf width at isocenter.* The width of the x-ray attenuation of a leaf at isocenter is sensitive to the source-to-MLC distance, and it should be verified during acceptance. The errors in leaf position can be compensated for using software corrections at the time the apertures are configured. However, for the sake of uniformity among machines, this condition should be corrected during installation of the MLC.

*Leaf position calibration.* Different techniques are used by the various vendors to calibrate the MLC leaf-position encoders. The Elekta system is calibrated by a procedure that requires setting the leaves to known positions to establish a look-up table to translate the pixel addresses of the leaf ends obtained from the optical image of the leaves, to the leaf positions in the plane of isocenter. The Varian system employs a collimated optical beam that is projected across the paths of the leaf ends. Each time the MLC control system is rebooted, the individual leaves are extended, one at a time, until they block the beam. The procedure resets registers associated with the individual shaft encoders. The register contents are used along with parameters established at the time of installation to determine the physical position of the leaves. The translation to the projection of the leaves to isocenter is then accomplished using a look-up table. The manufacturer's calibration procedures should be verified by checking the projected leaf positions over the entire range of travel of the leaves. Where calibration parameters are maintained in a file on the computer, these values should be recorded by the user and checked periodically. In the event that the leaves require recalibration by the user, a check of these stored values is recommended before proceeding. The calibration should be checked periodically during acceptance to observe the stability of the calibration with time. It is recommended that the leaves be exercised for at least several hours, perhaps overnight if there is an option to do this automatically.

MLCs with curved leaf faces produce a radiation field which has its 50% fluence point shifted under the leaf. Furthermore, this offset might be different as the leaves traverse the field. A multiple-exposure technique has been suggested for determining the position of the 50% fluence point relative to the physical leaf end.

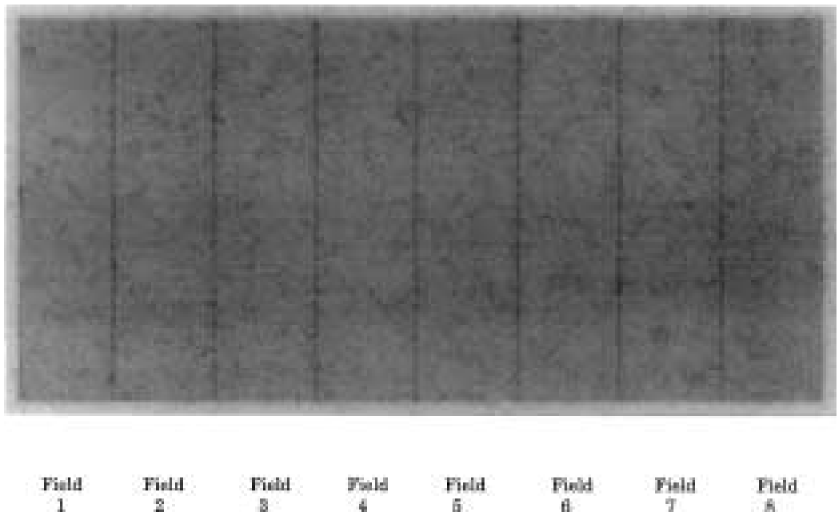


**Figure 11.** Diagram showing the alignment of 5-cm wide strips formed by the MLCs irradiating abutting rectangular fields. The degree of dose uniformity along the match lines is a sensitive measure of the alignment of the leaf position indicators, the light field, and the radiation field.

Radiographic film is placed in the plane of isocenter at full buildup. One should expose the film to 8 fields set by the MLC leaves (e.g., 5 cm × 40 cm centered every 5 cm) using equal monitor units sufficient to produce a net optical density of approximately 0.75 (see Figure 11). The match line for any two fields is placed at 5-cm intervals from the beam center axis. The leaves for the right side of the left-most field in Figure 11 (Field 1) are extended 15 cm over the midline for the first exposure. The leaves on the left side are drawn back 20 cm from midline (the maximum retraction). The leaf positioning should be checked with graph paper on the treatment table at the isocenter distance during the film measurements. For the Varian system and focused leaves, the leaves should move to their nominal positions. Leaves of the Phillips MLC (adjusted to the 50% fluence line) should extend beyond these positions slightly. A piece of graph paper placed on the treatment table at isocenter distance can be used to check the travel of the light field. The multiple exposure film should show dose homogeneity along the match lines for both systems. Any leaves out of alignment with their neighbors will be immediately obvious. Deviation of the net optical density along the match line of about 20% above or below the average net optical density indicates a positioning problem. The Elekta MLC should also produce a relatively smooth distribution since the round leaves are intentionally overlapped by a small amount. The Varian MLC, for which the light field edges should abut, are expected to produce a more dense region along the match line (to about 20% above the average net optical density). The film can be scanned along a line perpendicular to the high-density region using a microdensitometer. This scan will show a peak, which can be analyzed to determine the distance inside the leaf where the fluence falls to 50%. This is approximately equal to 1/2 the FWHM (full width at half maximum) of the peak after the density well away from the match line has been subtracted. The distance should be approximately 0.5 mm for the 15 MV beam on a Varian 2100C unit (Galvin, Smith, and Lally 1993). The offset of the 50% position relative to the point where the tangent line touches the leaf face might be different for various positions of the leaves in the field. This is because some collimators use end shapes that do not follow a smooth curve. For example, the Varian collimator has a flat portion on the leaf face. This test is also sensitive to other parameters such as the leaf calibration accuracy and variations in the light and radiation coincidence with position in the field.

*Leaf travel.* The leaves and/or carriages should reach their maximum specified ranges in both directions.

*Leaf speed.* The maximum speed of leaves and/or carriages should be verified. The individual leaves should move in a continuous smooth motion over their range of travel. Leaves which lag behind may be indicative of a problem which could lead to failure of the MLC and should be addressed as soon as possible.

*Transmission.* Leaf transmission, inter-leaf transmission, and transmission beneath leaves and jaws combined should be measured and compared to the manufacturer's specifications. This can be accomplished with a variety of methods. For example, with the jaws set to a 10-cm $\times$ 10-cm field, the leaves are first retracted to obtain a reference dose and then completely closed such that their faces are blocked by the jaws. If a calibrated film scanning system is available, then mid-leaf and inter-leaf variations can be quantified directly from film exposed to open and closed MLC fields. Alternately, a large-area ion chamber can be used to measure the average transmission over several adjacent leaves. Film should be used in any case to ensure that the maximum interleaf transmission is within acceptable limits.

Mid-leaf and inter-leaf transmissions should be performed at multiple gantry and collimator angles, particularly at configurations in which the interleaf spaces are horizontal to the floor (i.e., leaf sides "hang" with gravity). These tests should also be performed with the leaves at their extreme negative location (i.e., travel across central plane).

*Leakage between leaf faces in the closed position.* The radiation beam cannot be completely blocked by closing opposed leaf pairs of the MLC, especially when rounded leaves are used. Even when the leaves are allowed to touch, the fact that the 50% fluence line lies inside the leading edge of the round face allows an increased amount of radiation to pass. This situation is made worse when an additional gap is used to avoid mechanical contact of opposed leaves when closed. In order to minimize the unattenuated beam through this gap, the width of the gap on the central axis should be checked. This can be done for gaps on and off the axis by using film. For this reason, when it is necessary to close the leaves, the junction point is usually protected with one of the secondary jaws or by means of one of the follower collimators on the Philips system. If it is not possible to protect the junction, it is best to close the leaves away from the beam centerline. In this way, the direct line of sight between the opposed leaves will be reduced, and the fan rays produced for multiple treated fields will not intersect along the same line as the gantry is rotated.

### *d) Field-Shaping Software*

Any commercial software used to create irregularly shaped fields should be thoroughly tested before clinical implementation. Users should test all input devices, preprogrammed shapes and manipulations, program and display accuracies, etc. Attached input and output devices should be checked to ensure that spatial dimensions are accurately acquired and returned.

If an MLCPPS is used, the accuracy of the MLC leaf placement depends on the accuracy of the film digitizing system. Recommended manufacturer calibration procedures must be followed to assure consistent digitization accuracy. For commissioning, regular geometric fields should be digitized and the resulting MLC leaf positions checked to identify problems with identification of the origin and the scale. For example, a series of square contours should be digitized centered on the center of a tablet digitizer starting with a 10-cm × 10-cm field and extending in 10-cm increments up to the maximum size of the digitizer tablet. Any internal digital representations of the contours should be checked against the input dimensions where possible. Then the square contours should be plotted and the results checked against the original input contours. A similar set of tests should be devised for a raster scanning digitizer. MLC shape files should be generated from these contours. The files should then be used to set a series of MLC fields, and the light fields and radiation fields produced by the files should be checked. The match between input and field shape should be consistent with the manufacturer's specifications. As a final check, a series of typical irregular field shapes should be digitized and compared to readouts, optical shapes, and radiation shapes.

## B. Commissioning

### *a) Transmission*

The average of leaf and interleaf transmissions should be less than 2% although the maximum transmissions are 1%–2% higher between leaves for some of the commercially available MLCs. For the purposes of planning treatments, the average transmission is sufficient.

### *b) Central Axis Profiles*

The same dosimetry data that is used for conventional collimators must be either shown to apply to the MLC-shaped fields, or else the reasons for the discrepancies determined. At least a subset of the central axis tissue-phantom ratios (TPRs) [or tissue-maximum ratios (TMRs)] or percentage depth dose (PDD) should be checked.

### *c) Penumbra*

Small variations in penumbra are measurable for flat focused leaf ends. Rounded leaf ends have slightly broader penumbra due to increased transmission through the thinner leaf ends. The desirability to incorporate MLC penumbra into treatment planning beam data is dependent upon the planning system's capabilities, the use to which the profiles will be applied, and the frequency with which the MLC will be used. Beam profiles should be measured with special care taken to acquire accurate data in the penumbra region. The profiles of both symmetric and some asymmetric fields should be acquired to check the off-axis ratios (OARs). If possible, treatment-planning data should be augmented with OARs measured with the MLC.

## C. Safety Assessment

The assessment of safety with accelerators and associated devices is tested only minimally in a manufacturer's acceptance procedures. Additional safety tests are warranted because of the increased complexity of an MLC. The use of multiple, conformed MLC fields in either static or dynamic modes will render the conventional use of visual inspection as a daily verification of field shapes impractical or impossible. Active interlock checks should be carried out for leaf and jaw positional tolerances. These measurements should include assessment of software interlocks, hardware interlocks, and other possible independent systems. Nonactive interlocks designed to prevent unauthorized motions should be tested. These would include procedures such as dynamic imaging of field shape, motion enable power line interrupt, etc. Communication link interlocks are provided to ensure that the heavy data traffic that flows between the control computers and the accelerator hardware is not corrupted. Means of intentionally corrupting the data should be carefully discussed with the manufacturer. Tests should be devised to demonstrate that the interlocks are functioning to detect true positive data errors. Interlock checks to ensure the software will not allow a trailing edge of a leaf to be unshielded by the jaws must be performed.

**Table 3.** Multileaf Collimation Quality Assurance*

| Frequency | Test | Tolerance |
|---|---|---|
| Patient Specific | Check of MLC-generated field vs. simulator film (or DRR) before each field is treated | 2 mm |
| | Double check of MLC field by therapists for each fraction | Expected field |
| | On-line imaging verification for patient on each fraction | Physician discretion |
| | Port film approval before second fraction | Physician discretion |
| Quarterly | Setting vs. light field vs. radiation field for two designated patterns | 1 mm |
| | Testing of network system | Expected fields over network |
| | Check of interlocks | All must be operational |
| Annually | Setting vs. light vs. radiation field for patterns over range of gantry and collimator angles | 1 mm |
| | Water scan of set patterns | 50% radiation edge within 1 mm |
| | Film scans to evaluate interleaf leakage and abutted leaf transmission | Interleaf leakage <3%, abutted leakage <25% |
| | Review of procedures and in-service with therapists | All operators must fully understand operation and procedures |

*This table is reproduced in part from Klein, Low, and Purdy (1996).

Other interlocks provided to prevent the linac from damaging itself should be checked. These interlocks are highly vendor dependent and their tests will need to be designed based on a clear understanding of what interlocks have been provided and how they work. A discussion of all the interlocks provided by the various vendors is beyond the scope of this report. Such interlocks generally include detection of motor stalls, software detection of potential leaf collisions, etc.

For routine QA, we have outlined a quarterly and annual program that ensures accuracy, consistency, and checks for interlocks and the MLC's durability. A summary of checks is found in Table 3. An important aspect of a QA program is routine in-services to therapists. Performing only an introductory in-service prevents finding out about problems before they happen. Feedback from therapists is essential in evaluating the need for changes in written procedures, software settings, and requests for future modifications by manufacturers.

# 4. CLINICAL APPLICATIONS

## A. Leaf Placement Strategies

To realize the potential benefits of MLCs, it is important that their use be incorporated into the planning process as efficiently as possible. Manual placement of each of the 52 to 80 leaves that define an MLC portal is unacceptably time-consuming. Thus, some automated method embedded in a treatment planning system or using an MLCPPS as described above must be employed. Treatment planning systems are becoming available that can be used to define MLC fields that conform to BEV projections of planning target volumes (PTVs). The prescription procedures using the MLCPPS generally parallel the conventional ones using cerrobend blocks. More specifically, the MLC prescription procedures are carried out by means of the following steps:

### *a) Definition of Target Area*

MLC leaf positions have been based on a variety of criteria. These optimization criteria can be categorized as geometric and dosimetric. Rotation and translation of the collimator are often required for the best conformation. The best collimator angle can be set automatically by an algorithmic search through all the possible angles, or it can be set manually. The MLCPPS must consider all the physical constraints of the MLC system so that the prescribed leaf positions can be delivered. Interactive manual adjustments of individual leaves and other parameters are often necessary.

Geometric methods align each leaf with the continuous contour of the portal aperture or with the projection of the PTV (ICRU 1993) as indicated on a simulation film or DRR by a radiation oncologist. The determination of the target volume is, of course, critical to the success of the therapy. The MLC should then be set to define the treated volume (ICRU 1993). It is essential that a clear understanding exist of the interpretation and significance of the contour to which the MLC leaves are set. The target area is defined based on the prescription image. For conventional radiation therapy, the prescription image is the simulation film and the physicians draw field prescriptions directly on films.

### *b) Optimization of MLC Conformation*

Assuming that a clear understanding of the interpretation of the field outline contour has been established, the boundary of the treatment volume, projected in the direction of the field to be collimated, can be digitized by one of the several methods available to create a closed contour defined by a finite set of points, $x_j$ and $y_j$.

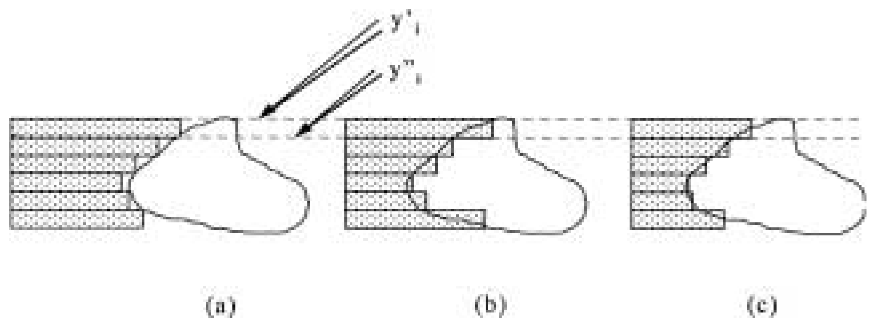


**Figure 12.** Illustration of three strategies for positioning MLC leaves at the nominal field boundary. (a) “out-of-field placement,” (b) “in-field” placement, (c) “cross-boundary” placement.

The technical problem is to determine the best positions for the MLC leaves. The use of cerrobend blocks to form tertiary field margins has provided radiation oncologists a means of continuously matching the boundary of the collimation with the projection of the treated volume. However, when MLCs are used, the collimation occurs in discrete steps.

To determine the optimal position of the leaves automatically with a computer algorithm, several treatment machine-dependent characteristics must be made known to the algorithm, such as the number of leaves, their widths, travel limits, source-to-MLC distance, and relative leaf travel direction. Then the MLC (and jaws) may be placed relative to the target contour shape. Three leaf coverage strategies that have been used are illustrated in Figure 12. In this figure the leaves are shown shaded and placed relative to the desired effective treatment field contour. The three classes of strategies are the “out-of-field” strategy illustrated in panel (a), the “in-field” strategy illustrated in panel (b), and “cross-boundary” strategies typified in panel (c). Each strategy uses the intersections of the effective field contour with the projections of the trajectories of the sides of the ith leaf. The trajectories of the sides of the ith leaf are indicated by $y_i'$ and $y_i''$ in Figure 12. The intersections of the treatment field contour with the trajectories of the leaf sides will be denoted by $x_i'$ and $x_i''$. The out-of-field strategy avoids shielding any part of the projected treatment volume. This strategy has been recommended as being the most conservative because it avoids shielding any part of the treatment volume.

Tighter coverage than the continuous aperture occurs when the in-field strategy illustrated in Figure 12 by panel (b) is used. This approach is conservative with respect to normal structures that abut the treatment volume. It may be useful for 3-D multiple field techniques when other fields are added, where the isodose lines in the BEV plane for a single field shift outward.

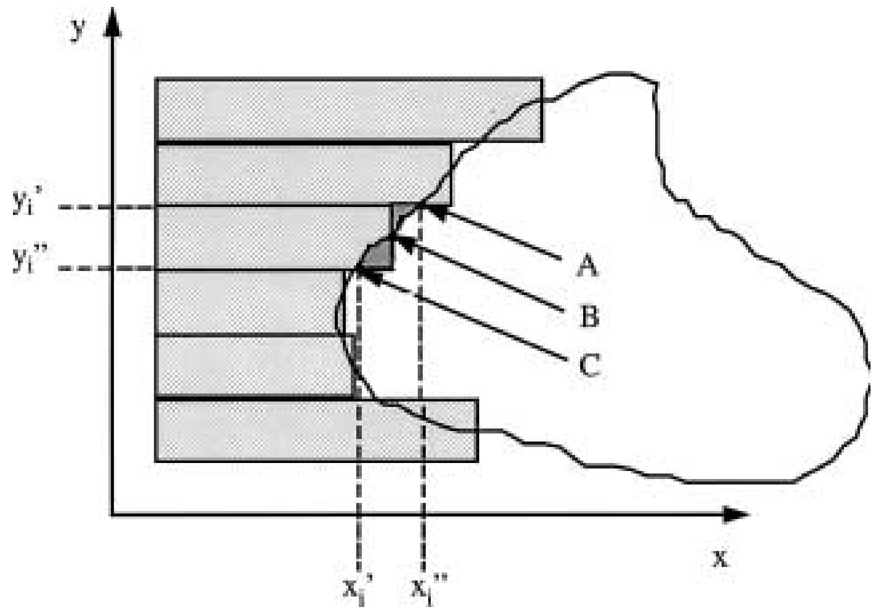


**Figure 13.** Demonstration of the "out-of-field" area between A and B and the "in-field" area between B and C.

The most widely used methods are cross-boundary techniques indicated in panel (c) of Figure 12. One must specify mathematically what one considers to be the optimum condition for positioning the leaves. In Figure 13 the intersections of the projections of the leaf lying between $y_i'$ and $y_i''$ with the treatment field contour are the points A and C. One criterion that has been used is to minimize the sum of the out-of-field area between A and B, and the in-field area between B and C in Figure 13. It can be shown (Frazier et al. 1995a) that this criterion is met when the leaf position is selected such that the treatment field contour bisects the projection of the leaf end. The mathematical implementation consists of finding the intersection of the treatment field contour with the line represented by $y = (y_i' + y_i'')/2$. For convex field contours, minimizing the sum of the in-field and out-of-field areas results in an unblocked out-of-field area between A and B that is greater than the MLC-blocked in-field area between B and C. For concave field contours the same procedure results in an in-field area that is greater than the out-of-field area.

Another condition for optimizing the leaf position has been the criterion that the in-field area be equal to the out-of-field area (LoSasso et al. 1993). This is equivalent to minimizing the least-square difference between the leaf end and the contour segment in the leaf track (Yu et al. 1995). The value of *x* to which the leaf is set is then

$$x = \frac{\int_{y_i'}^{y_i''} f(y)dy}{y_i'' - y_i'} \tag{4}$$

The leaf is set to a point B in Figure 13 that has the properties that the area of the treatment field projection shielded by the leaf (the horizontal shading between B and C) is equal to the area outside the projection of the treatment field (the vertical shading between A and B). Since most radiation fields have more convex intersections with leaves than concave intersections, having the treatment field contour simply bisect the end of the leaf usually produces collimation that encroaches less into radiation field than equalizing the in-field and out-of-field areas (Frazier et al. 1995a).

The leaves at the upper and lower margins of the field must be handled as special cases. At these limits, the photon jaws can be placed exactly tangent to the treatment field contour. For both the all leaves in-field and the all leaves out-of-field strategies, the extreme leaves may then be set using the out-of-field method. This will avoid leaf settings that call for an overlap condition. For the cross-boundary method, the superior and inferior leaves may be handled as if their leaf width extended only from the leaf's in-field edge to the projection of the photon jaw.

## B. Techniques for Determining the Leaf Positions

The prescribed field shape and the MLC leaf positions are normally displayed for verification of correct MLC conformation. It is also desirable to have dosimetric information overlaid on the prescription image. If the MLCPPS contains a raster digitizer, it can be made to serve as a film dosimetry system (Du et al. 1994). Isodose contours can be calculated from in-phantom film measurements of the MLC-conformed field at the prescription depth and overlaid onto the digitized simulator film image. Fast BEV isodose calculation can also be incorporated into the MLCPPS to provide instant evaluation of MLC prescriptions.

It may also be desirable to verify the stepped field shape of MLC during treatment simulation. A few models of MLC simulation have been proposed (Karlsson 1994). One approach is to project the MLC field shape using an LCD (liquid crystal display) device placed in the light field during treatment simulation. Physical leaves have also been constructed for the simulator to set the desired leaf positions (Klein et al. 1995).

There may be occasions when cerrobend blocks must be used when the field shapes are too complex for the MLC to conform without introducing gross errors. A Y-shaped field is such an example. Field-splitting (i.e., division of a field into simpler sub-fields) is necessary if the MLC is required to completely replace cerrobend blocks for beam shaping. The MLC flexibility in field shaping seems to make this easily applicable. Good mechanical calibration of the MLC is crucial to the field-splitting approach because the border regions of the sub-fields, unlike the penumbra region, are highly sensitive to the precision of the leaf position calibration. Further study on the effects of patient motion between sub-fields is required to ensure the safety and accuracy of this approach.

Regardless of the automatic technique used, the MLC aperture shape may not be logical when evaluated by the treatment planner. It is generally necessary to adjust individual leaves to ensure target coverage in a critical region or to avoid small critical structures that may be close to a target volume. If this is not possible, alloy shaping may be the best solution. A manual leaf adjustment facility should be provided using the BEV technique. The projections of the leaves should be overlaid on the original simulation film or on a DRR such that individual leaves can be repositioned according to the judgment of the treatment planner.

Where BEV dose distributions and dose volume histograms (DVHs) are available, leaves can be adjusted based upon actual coverage of target and normal tissues. This involves the manual adjustment of leaves in the BEV plane while the isodose distribution is updated, aided by DVHs and surface dose distributions. Ideally, this adjustment would be done automatically by the treatment planning computer. This approach requires a rather sophisticated treatment planning system with extremely fast computational capabilities.

## C. Optimization of Collimator Rotation

Rotation of the direction of leaf travel can optimize the fit of the leaf shape to treatment target volumes. An example is the alignment of the leaf faces with the cord axis when the cord is near the target. Geometric relationships based upon target shape or minimization of normal tissue integral dose can drive the optimization if critical structures are not the deciding factor.

Brahme's work (1988) considers the optimal choices of the collimator angle in order to optimize the leaf direction, depending on whether the field shape is convex, concave-convex, or contains multiple concavities. The one conclusion drawn by Brahme is that the optimal direction for the leaf motion is in the direction along the narrower axis. For a simple ellipse, the optimal leaf direction is parallel to the short axis. One group (Du et al. 1994) has developed a method for determining optimal leaf positioning in concert with optimal collimator angulation. Their optimization schema demands the following criteria be met: (a) the desired internal area is maintained, (b) the single leaf discrepancy is minimal, (c) that criteria (a) and (b) are combined to be minimal. The problem with collimator optimization is that wedges cannot be used at any desired angle of rotation unless two wedges are used with weights that produce a desired wedge rotation. Use of multiple weighted wedges introduces a level of complexity that decreases the feasibility of collimator optimization for MLCs.

## D. MLC Field Edge Accuracy Compared with Cerrobend

A few recent studies have compared the geometric accuracy and treatment variation of MLC and cerrobend. Frazier et al. (1995b) examined treatment variation with the resultant dosimetric beams eye view isodoses by using on-line portal images. LoSasso and Kutcher (1994) used analytical methods to compare the geometric accuracy of MLC-shaped fields with cerrobend-shaped fields. They found that the geometric accuracy of MLC is comparable and slightly superior to that of cerrobend even when considering the stepping effect of the leaves. Both studies concluded that cerrobend block treatments are susceptible to undetected fabrication errors. Klein et al. (1995) studied the effects of tissue heterogeneities on penumbra and the resultant field definition. Film placed at depth was imbedded in solid water, solid lung, or solid bone. The photon fluence to the film was maintained as equivalent proximal and distal effective depths were maintained. They found lung to increase penumbra (especially 18 MV photons) and bone to decrease penumbra for both cerrobend and MLC. But the relatively small increase in the MLC-generated penumbra compared to the cerrobend-generated penumbra did not increase due to the presence of lung. Evaluation of superposition of opposed fields with MLC- and cerrobend-shaped fields consistently showed superior superposition for the MLC fields, despite the stair-stepping effects (Klein et al. 1995). The use of 3-D planning allows dose comparisons to be made with conventional cerrobend shaping. Powlis et al. (1993) calculated DVHs for alloy-shaped fields and compared them to the same fields shaped by MLC. They also presented comparative DVHs for target coverage and organ sparing when the number of treatment fields increases (i.e., 10-field prostate plans), with the mindset that the use of MLC affords an efficient increase in the daily number of fields. The resultant DVHs show little difference when comparing the plans for which the fields were shaped using cerrobend with the plans for which the fields were shaped using the MLC, and there were greatly improved DVHs when the number of fields were increased. Their work concluded that improved local control would be facilitated with the use of MLC. Brahme (1993) has considered the importance of increasing the number of fields, but placed it in minor relevance compared with the potential of MLC in terms of intensity-modulated beams and the future of dynamic conformal therapy. LoSasso and Kutcher (1994) studied the differences in tumor control probability (TCP) and normal tissue compilation probabilities (NTCP) when cerrobend and MLC were used. They found the differences to be negligible in treatment of the prostate and nasopharynx, especially when treatment uncertainty was built into the calculation model.

Physicians, physicists, and others evaluating dose distributions and portal films with radiation therapy fields should understand that the penumbra in a patient is not as sharp as a portal image would indicate. Electron transport and photon scatter at the field edge and the influences of multiple fields and patient setup uncertainties reduce the dose gradient at the edge of the target volume, although these latter factors are usually not considered when quantifying penumbra. These diffusing effects occur for both smooth and MLC apertures. For MLC, these effects take on an added role of smoothing the stepped nature of the dose distribution, which is an important issue in the opinion of many users. Unfortunately, the appearance of the MLC, as imaged, often affects the willingness of the therapy community to use MLC as a replacement for blocks. The concept of the "effective penumbra," for a single field, in a reproducible phantom geometry, does an injustice to MLC in comparison with blocks, when considered in the context of clinical usage.

If the dose coverage of the target volume provided by the MLC aperture appears inadequate, then factors other than the positions of the leaves may be responsible. For example, narrow regions of the field, especially at large depth and low energies, are often underdosed due to decreases in photon scatter relative to the prescription point. In such a situation, manipulation of the leaves locally in a reasonable manner will not rectify the underdosage. Furthermore, it will be difficult to determine the appropriate position of the leaves using dose-based registration since the isodose level being prescribed to may not extend into this region. By manually adjusting the leaves, one can confirm whether the underdosage is MLC induced, although such a situation is usually obvious to the experienced planner. The solution for the leaf alignment is to adjust the leaves until the local dose gradient in this region is comparable to other portions of the target. The underdosage between regions of the target would then require compensation within the field or in conjunction with other fields, where possible, as with continuous apertures. "Island" blocking with MLC is possible, but a bit laborious without support of the use of MLCs with an information management system or the use of dynamic MLC software. At least two composite fields would be required. In order to shield the desired internal island region, an additional portion of the desired treated field would be shielded, as the leaves must extend from the periphery to the island. Therefore, the shielded portion, which needs treatment, requires a separate added field. The matching of the first field with the compensatory field is a disadvantage of this technique.

## 5. QUALITY ASSURANCE (QA)

### A. Port Film/Light Field Checks

MLC leaf position files can be created by either digitization methods or by a direct generation of leaf positions by 3-D radiotherapy treatment planning (3-DRTP) system. The files are eventually transferred over a network system (or by disk transfer) to the MLC controller and workstation at the treatment machine. Prior to use, each field should be compared with the original simulation film or

DRR. A match of light field and original shaped field should be within 2 mm for all boundaries. If the field is drawn on the patient's skin or immobilization device, the light field of the field shaped by the MLC should also project at all boundaries to within 2 mm. Some facilities may opt to forego simulating MLC fields (in the case of a field reduction) and treat directly with the MLC-shaped field. In this case, a port film should be acquired and approved before continuation of the treatment. The jaw settings and field name must also be checked. Inappropriate jaw settings could block a portion of the desired field, or generous settings could leave a trailing leaf region unblocked. Once the fields and relevant information (patient, field name) are checked, the MLC files may then be released for treatment. Electronic portal imaging devices are particularly useful for quickly and conveniently checking MLC-shaped fields.

## B. Record and Verify (R&V) Computer Checks

Commercial information management systems are becoming available that offer a module designed to check the MLC fields. These systems will facilitate the selection and transfer of the correct patient and field to the machine control computers. The systems may also check the individual leaf settings versus actual positions. The physicist must then assign tolerance levels for leaf position accuracy. A tolerance of 0.5 mm is a minimum for the MLCs with widths on the order of 1 cm. For the nonconventional MLCs with leaves on the order of a few millimeters, the maximum allowable tolerance should be about 0.5 mm.

One institution that has an "eavesdrop" MLC Record and Verify (R&V) system found average deviations of 0.6 mm over approximately 10,000 histories (Mageras et al. 1994). This system works as follows. For MLC fields planned on the 3-D planning computer, treatment planning software generates an MLC file containing the leaf positions. This file is copied to the MLC computer and to an independent disk directory for use by the R&V system. The therapists enter the treatment prescription that includes the MLC file name and the beam name for each field into the R&V system before the first treatment. Before daily treatments, the therapist selects the appropriate patient and field from the MLC computer and from the R&V system. The MLC is physically positioned based upon the settings in the MLC computer, although manual adjustments are permitted. When an attempt is made to turn the beam on, the R&V system acquires the physical leaf positions from the treatment machine. It then compares the setup values to those found in the MLC file for this field (as defined in the prescription). If there is a discrepancy, a failure occurs. Also, if either the MLC file name or the beam name is not found, a failure occurs. Patients not planned with the 3-D planning computer are handled differently. An MLC file is copied to the MLC computer, but is not copied to R&V. At the time of treatment setup, R&V acquires the settings for each field and creates an MLC file to be used for all subsequent treatments. Modern commercial R&V information systems integrate the MLC fields as part of the treatment fields, avoiding the need for interaction by the accelerator operator with an additional MLC workstation.

Using computer files instead of physical blocks is a process that must be implemented with care. Physical blocks are identified with printed labels, whereas MLC field-shape files are identified with file names. In principle, there is no difference between a label printed on a blocking tray and a computer file label. However, personnel who are unaccustomed to using computers as they try to identify and use computer file labels can introduce errors. Since R&V information management systems can be used to link specific MLC field-shape files to identify treatment fields, individual MLC files do not need to be selected each time a patient is treated. Using these systems, the MLC file is automatically loaded into the MLC controller when the identified field is selected within the R&V system. Once the link between the treatment field and the MLC field-shape file has been verified, the field can be treated for the prescribed number of fractions with reasonable certainty that the correct shape will be used each time. For this reason it is recommended that R&V systems be implemented whenever MLCs are used.

## 6. POTENTIAL FOR THE FUTURE

Treatment of shaped portals by the use of an MLC is more efficient than by tray-mounted blocks, especially when MLC field-shape files are saved and retrieved from an information management system. The efficiency gain has allowed the implementation of conformal therapy. In addition, computer-controlled MLCs can be used to implement various forms of dynamic therapy including intensity-modulated conformal therapy. However, these applications are beyond the scope of the current report.

Networking is perhaps the most rapidly expanding application of computer engineering. The accelerator manufacturers are offering networking systems to integrate the planning, delivery, verification, and record keeping into a single departmentwide program. These systems can manage treatment verification data and can integrate images as well. When these functions are implemented with DICOM3-RT standards, it should be possible to integrate systems provided by different vendors into the same program.

It now seems feasible that off-the-shelf systems that employ MLCs can now, or will soon, be integrated into programs that fit the individual needs and resources of a wide range of therapy facilities. Such programs will be implemented and tested over the next few years.

## 7. REFERENCES


Ahnesjo, A. (1994). "Analytical modeling of photon scatter from flattening filters in photon therapy beams." *Med. Phys.* 21: 1127–1235.

Ahnesjo, A. (1995). "Collimator scatter in photon therapy beams." *Med. Phys.* 22: 267–278.

Ahnesjo, A., T. Knoos, and A. Montelius (1992). "Application of the convolution method for calculation of output factors for therapy photon beams." *Med. Phys.* 19: 295–302.

Boyer, A. L., T. G. Ochran, C. E. Nyerick, T. J. Waldron, and C. J. Huntzinger (1992). "Clinical dosimetry for implementation of a multileaf collimator." *Med. Phys.* 19: 1255–1261.

Brahme, A. (1988). "Optimal setting of multileaf collimators in stationary beam radiation therapy." *Strahlenther. Onkol.* 164: 343–350.

Brahme, A. (1993). "Optimization of radiation therapy and the development of multi-leaf collimation." *Int. J. Radiat. Oncol. Biol. Phys.* 25: 373–375.

Carol, M. P. (1992). "An automatic 3-D treatment planning and implementation system for optimized conformal therapy by the NOMOS Corporation." *Int. J. Radiat. Oncol. Biol. Phys.* 23: 1081.

Chaney, E. L., T. J. Cullip, and T. A. Gabriel (1994). "A Monte Carlo study of accelerator head scatter." *Med. Phys.* 21: 1383–1390.

Clarkson. (1941). "A note on depth dose in fields of irregular shape." *Br. J. Radiol.* 14: 165.

Day, M. J., and G. A. Aird (1983). "The equivalent-field method for dose determinations in rectangular fields." *Br. J. Radiol.* (*Suppl.*) 17: 105–114.

Du, M. N., C. X. Yu, M. Symons, D. Yan, R. Taylor, R. C. Matter, G. Gustafson, A. Martinez, and J. W. Wong (1994). "Multileaf collimator prescription preparation system for conventional radiotherapy." *Int. J. Radiat. Oncol. Biol. Phys.* 30: 707–714.

Dunscombe, P.B., and J. M. Nieminen (1992). "On the field-size dependence of relative output from a linear accelerator." *Med. Phys.* 19: 1441–1444.

Duzenli, C., B. McClean, and C. Field (1993). “Backscatter into the beam monitor chamber: Implications for dosimetry of asymmetric collimators.” *Med. Phys.* 20: 363–367.

Frazier, A., M. Du, J. Wong, F. Vicini, R. Taylor, C. Yu, R. Matter, A. Martinez, and D. Yan (1995a). “Dosimetric evaluation of the conformation of the multileaf collimator to irregularly shaped fields.” *Int. J. Radiat. Oncol. Biol. Phys.* 33: 1229–1238.

Frazier A., D. Yan, M. Du, J. Wong, F. Vicini, R. Matter, M. Joyce, and A. Martinez (1995b). “Effects of treatment setup variation on beam’s eye view dosimetry for radiation therapy using the multileaf collimator vs. the cerrobend block.” *Int. J. Radiat. Oncol. Biol. Phys.* 33: 1247–1256.

Galvin, J. M., A. Smith, and B. Lally (1993). “Characterization of a multi-leaf collimator system.” *Int. J. Radiat. Oncol. Biol. Phys.* 25: 181–192.

Galvin, J. M., X.-G. Chen, and R. M. Smith (1993). “Combining multileaf fields to modulate fluence distributions.” *Int. J. Radiat. Oncol. Biol. Phys.* 27: 697–705.

Galvin, J. M., A. R. Smith, R. D. Moeller, R. L. Goodman, W. D. Powlis, J. Rubenstein, L. J. Solin, B. Michael, M. Needham, C. Huntzinger, and M. Kligerman (1992). “Evaluation of multileaf collimator design for a photon beam.” *Int. J. Radiat. Oncol. Biol. Phys.* 23: 789–780.

Glasgow, G. P. (1980). “Safety considerations during the production of radiation therapy shielding blocks from low melting temperature bismuth alloys” in *Health Physics Society Mid-year Symposium.*

Huang, P. H., J. Chu, and B. E. Bjarngard (1987). “The effect of collimator backscatter radiation on photon output of linear accelerators.” *Med. Phys.* 14: 268–269.

Huq, M. S., Y. Yu, Z. P. Chen, and N. Suntharalingam (1995). “Dosimetric characteristics of a commercial multileaf collimator.” *Med. Phys.* 22: 241–247.

International Commission on Radiation Units and Measurements (ICRU) Report 50. “Prescribing, Recording, and Reporting Photon Beam Therapy.” (Andre Allisy, chairman). Bethesda, MD: ICRU, 1993.

Jaffray, D. A., J. J. Battista, A. Fenster, and P. Munro (1993). “X-ray sources of medical linear accelerators: Focal and extra-focal radiation.” *Med. Phys.* 20: 1417–1427.

Jordan, T. F., and P. C. Williams (1994). “The design and performance characteristics of a multileaf collimator.” *Phys. Med. Biol.* 39: 231–251.

Karlsson, M. A. (1994). “A multileaf delineator system for a radiotherapy simulator.” *Med. Phys.* 21: 83–84.

Kase, K. R., and G. K. Svensson (1986). “Head scatter data for several linear accelerators (4-18 MV).” *Med. Phys.* 13: 530–532.

Klein, E. E., D. A. Low, and J. A. Purdy (1996). “A quality assurance program for ancillary high-technology devices on a dual-energy accelerator.” *Radiother. Oncol.* 38: 51–60.

Klein, E. E., W. B. Harms, D. A. Low, V. Willcut, and J. A. Purdy (1995). “Clinical implementation of a commercial multileaf collimator: Dosimetry, networking, simulation, and quality assurance.” *Int. J. Radiat. Oncol. Biol. Phys.* 33: 1195–1208.

Kubo, H. (1989). “Telescopic measurements of backscattered radiation from secondary collimator jaws to a beam monitor chamber using a pair of slits.” *Med. Phys.* 16: 295–298.

Lam, K. L., M. S. Muthuswamy, and R. K. Ten Haken (1996). “Flattening-filter-based empirical methods to parametrize the head scatter factor.” *Med. Phys.* 23: 343–352.

LoSasso, T., and G. J. Kutcher (1994). “Multileaf collimation vs. cerrobend blocks: Analysis of geometric accuracy.” Submitted to *Int. J. Radiat. Oncol. Biol. Phys.*

LoSasso, T., C. S. Chui, G. J. Kutcher, S. A. Leibel, Z. Fuks, and C. C. Ling (1993). “The use of a multi-leaf collimator for conformal radiotherapy of carcinomas of the prostate and nasopharynx.” *Int. J. Radiat. Oncol. Biol. Phys.* 25: 161–170.

Luxton, G., and M. A. Astrahan (1988). “Output factor constituents of a high-energy photon beam.” *Med. Phys.* 15: 88–91.

McKenzie, A. L., and P. H. Stevens (1993). “How is photon head scatter in a linear accelerator related to the concept of a virtual source?” *Phys. Med. Biol.* 38: 1173–1180.

Mageras, G. S., Z. Fuks, J. O'Brien, L. J. Brewster, C. Burman, C. S. Chui, S. A. Leibel, C. C. Ling, M. E. Masterson, R. Mohan, and G. J. Kutcher (1994). "Initial clinical experience with computer-controlled conformal radiotherapy of the prostate using a 50 MeV medical microtron." *Int. J. Radiat. Oncol. Biol. Phys.* 30: 971–978.

Maleki, N., and P. K. Kijewski (1983). "Analysis of the field defining properties of a multi-leaf collimator." (Abstract). *Med. Phys.* 10: 518.

Palta, J. R., D. K. Yeung, and V. Frouhar (1996). "Dosimetric considerations for a multileaf collimator system." *Med. Phys.* 23: 1219–1224.

Patterson, M. S., and P. C. Shragge (1981). "Characteristics of an 18 MV photon beam from a Therac 20 medical linear accelerator." *Med. Phys.* 8: 312–318.

Powers, W. E., J. J. Kinzie, J. A. Demidecki, J. S. Bradfield, and A. Feldman (1973). "A new system of field shaping for external-beam radiation therapy." *Radiol.* 108: 407–411.

Powlis, W. D., A. R. Smith, E. Cheng, J. M. Galvin, F. Villari, P. Bloch, and M. M. Kligerman (1993). "Initiation of multi-leaf collimator conformal radiation therapy." *Int. J. Radiat. Oncol. Biol. Phys.* 25: 171–179.

Sharpe, M. B., D. A. Jaffray, J. J. Battista, and P. Munro (1995). "Extrafocal radiation: A unified approach to the prediction of beam penumbra and output factors for megavoltage x-ray beams." *Med. Phys.* 22: 2065–2074.

Shiu, A. S., H. M. Kooy, J. R. Ewton, S. S. Tung, J. Wong, K. Antes, and M. H. Maor (1997). "Comparison of miniature multileaf collimation (MMLC) with circular collimation for stereotactic treatment." *Int. J. Radiat. Oncol. Biol. Phys.* 37: 679–688.

Takahaski, S. (1965). "Conformation radiotherapy-rotation techniques as applied to radiography and radiotherapy of cancer." *Acta Radiol. Suppl.* 242: 1–142.

Yu, C. X., D. Yan, M. N. Du, S. Zhou, and L. J. Verhey (1995). "Optimization of leaf positions when shaping a radiation field with a multileaf collimator." *Phys. Med. Biol.* 40: 305–308.

Zhu, T. C., and B. E. Bjarngard (1995). "The fraction of photons undergoing head scatter in x-ray beams." *Phys. Med. Biol.* 40: 1127–1134.

AAPM REPORT SERIES ($15.00 Each)

No. 1 "Phantoms for Performance Evaluation and Quality Assurance of CT Scanners" (1977)

No. 3 "Optical Radiations in Medicine: A Survey of Uses, Measurement and Sources" (1977)

No. 4 "Basic Quality Control in Diagnostic Radiology," AAPM Task Force on Quality Assurance Protocol (1977)

No. 5 "AAPM Survey of Medical Physics Training Programs," Committee on the Training of Medical Physicists (1980)

No. 6 "Scintillation Camera Acceptance Testing & Performance Evaluation, "AAPM Nuclear Medicine Committee (1980)

No. 7 "Protocol for Neutron Beam Dosimetry," AAPM Task Group #18 (1980) (FREE)

No. 8 "Pulse Echo Ultrasound Imaging Systems: Performance Tests & Criteria," P. Carson & J. Zagzebski (1980)

No. 9 "Computer-Aided Scintillation Camera Acceptance Testing," AAPM Task Group of the Nuclear Medicine Committee (1982)

No. 10 "A Standard Format for Digital Image Exchange," Baxter et al. (1982)

No. 11 "A Guide to the Teaching of Clinical Radiological Physics to Residents in Radiology," AAPM Committee on the Training of Radiologists (1982)

No. 12 "Evaluation of Radiation Exposure Levels in Cine Cardiac Catherization Laboratories," AAPM Cine Task Force of the Diagnostic Radiology Committee (1984)

No. 13 "Physical Aspects of Quality Assurance in Radiation Therapy," AAPM Radiation Therapy Committee Task Group #24, with contribution by Task Group #22 (1984)

No. 14 "Performance Specifications and Acceptance Testing for X-Ray Generators and Automatic Exposure Control Devices" (1985)

No. 15 "Performance Evaluation and Quality Assurance in Digital Subtraction Angiography," AAPM Digital Radiology/Fluorography Task Group (1985)

No. 16 "Protocol for Heavy Charged-Particle Therapy Beam Dosimetry," AAPM Task Group #20 of the Radiation Therapy Committee (1986)

No. 17 "The Physical Aspects of Total and Half Body Photon Irradiation," AAPM Task Group #29 of the Radiation Therapy Committee (1986)

No. 18 "A Primer on Low-Level Ionizing Radiation and its Biological Effects," AAPM Biological Effects Committee (1986)

No. 19 "Neutron Measurements Around High Energy X-Ray Radiotherapy Machines," AAPM Radiation Therapy Task Group #27 (1987)

No. 20 "Site Planning for Magnetic Resonance Imaging Systems," AAPM NMR Task Group #2 (1987)

No. 21 "Specification of Brachytherapy Source Strength," AAPM Radiation Therapy Task Group #32 (1987)

No. 22 "Rotation Scintillation Camera Spect Acceptance Testing and Quality Control," Task Group of Nuclear Medicine Committee (1987)

No. 23 "Total Skin Electron Therapy: Technique and Dosimetry," AAPM Radiation Therapy Task Group #30 (1988)

No. 24 "Radiotherapy Portal Imaging Quality," AAPM Radiation Therapy Task Group #28 (1988)

No. 25 "Protocols for the Radiation Safety Surveys of Diagnostic Radiological Equipment," AAPM Diagnostic X-Ray Imaging Committee Task Group #1 (1988)

No. 26 "Performance Evaluation of Hyperthermia Equipment," AAPM Hyperthermia Task Group #1 (1989)

No. 27 "Hyperthermia Treatment Planning," AAPM Hyperthermia Committee Task Group #2 (1989)

No. 28 "Quality Assurance Methods and Phantoms for Magnetic Resonance Imaging," AAPM Nuclear Magnetic Resonance Committee Task Group #1 (1990)

No. 29 "Equipment Requirements and Quality Control for Mammography," AAPM Diagnostic X-Ray Imaging Committee Task Group #7 (1990)

No. 30 "E-Mail and Academic Computer Networks," AAPM Computer Committee Task Group #1 (1990)

No. 31 "Standardized Methods for Measuring Diagnostic X-Ray Exposures," AAPM Diagnostic X-Ray Imaging Committee Task Group #8 (1991)

No. 32 "Clinical Electron-Beam Dosimetry," AAPM Radiation Therapy Committee Task Group #25 (1991)

No. 33 “Staffing Levels and Responsibilities in Diagnostic Radiology,” AAPM Diagnostic X-Ray Imaging Committee Task Group #5 (1991)

No. 34 “Acceptance Testing of Magnetic Resonance Imaging Systems,” AAPM Nuclear Magnetic Resonance Task Group #6 (1992)

No. 35 “Recommendations on Performance Characteristics of Diagnostic Exposure Meters,” AAPM Diagnostic X-Ray Imaging Task Group #6 (1992)

No. 36 “Essentials and Guidelines for Hospital Based Medical Physics Residency Training Programs,” AAPM Presidential AD Hoc Committee (1992)

No. 37 “Auger Electron Dosimetry,” AAPM Nuclear Medicine Committee Task Group #6 (1993)

No. 38 “The Role of the Physicist in Radiation Oncology,” Professional Information and Clinical Relations Committee Task Group #1 (1993)

No. 39 “Specification and Acceptance Testing of Computed Tomography Scanners,” Diagnostic X-Ray Imaging Committee Task Group #2 (1993)

No. 40 “Radiolabeled Antibody Tumor Dosimetry,” AAPM Nuclear Medicine Committee Task Group #2 (1993)

No. 41 “Remote Afterloading Technology,” Remote Afterloading Technology Task Group #41 (1993)

No. 42 “The Role of the Clinical Medical Physicist in Diagnostic Radiology,” Professional Information and Clinical Relations Committee Task Group #2 (1993)

No. 43 “Quality Assessment and Improvement of Dose Response Models,” $25, (1993)

No. 44 “Academic Program for Master of Science Degree in Medical Physics,” AAPM Education and Training of Medical Physicists Committee (1993)

No. 45 “Management of Radiation Oncology Patients with Implanted Cardiac Pacemakers,” AAPM Task Group #4 (1994)

No. 46 “Comprehensive QA for Radiation Oncology,” AAPM Radiation Therapy Committee Task Group #40 (1994)

No. 47 “AAPM Code of Practice for Radiotherapy Accelerators,” AAPM Radiation Therapy Task Group #45 (1994)

No. 48 "The Calibration and Use of Plane-Parallel Ionization Chambers for Dosimetry of Electron Beams," AAPM Radiation Therapy Committee Task Group #39 (1994)

No. 49 "Dosimetry of Auger-Electron-Emitting Radionuclides," AAPM Nuclear Medicine Task Group #6 (1995)

No. 50 "Fetal Dose from Radiotherapy with Photon Beams," AAPM Radiation Therapy Committee Task Group #36 (1995)

No. 51 "Dosimetry of Interstitial Brachytherapy Sources," AAPM Radiation Therapy Committee Task Group #43 (1995)

No. 52 "Quantitation of SPECT Performance," AAPM Nuclear Medicine Committee Task Group #4 (1995)

No. 53 "Radiation Information for Hospital Personnel," AAPM Radiation Safety Committee (1995)

No. 54 "Stereotactic Radiosurgery," AAPM Radiation Therapy Committee Task Group #42 (1995)

No. 55 "Radiation Treatment Planning Dosimetry Verification," AAPM Radiation Therapy Committee Task Group #23 (1995), $48, (Includes 2 disks, ASCII format). Mail, fax, or phone orders to: AAPM Headquarters, One Physics Ellipse, College Park, MD 20740-3846, Phone: (301) 209-3350, Fax: (301) 209-0862

No. 56 "Medical Accelerator Safety Considerations," AAPM Radiation Therapy Committee Task Group #35, Reprinted from *Medical Physics*, Vol. 20, Issue 4, July/August 1993

No. 57 "Recommended Nomenclature for Physical Quantities in Medical Applications of Light," AAPM General Medical Physics Committee Task Group #2 (1996)

No. 58 "Managing the Use of Fluoroscopy in Medical Institutions," AAPM Radiation Protection Committee Task Group #6 (1998)

No. 59 "Code of Practice for Brachytherapy Physics," AAPM Radiation Therapy Committee Task Group #56, Reprinted from *Medical Physics*, Vol. 24, Issue 10, October 1997

No. 60 "Instrumentation Requirements of Diagnostic Radiological Physicists," AAPM Diagnostic X-Ray Committee Task Group #4 (1998)

No. 61 "High Dose Brachytherapy Treatment Delivery," AAPM Radiation Therapy Committee Task Group #59, Reprinted from *Medica l Physics*, Vol. 25, Issue 4, April 1998

No. 62 “Quality Assurance for Clinical Radiotherapy Treatment Planning,” AAPM Radiation Therapy Committee Task Group #53, Reprinted from *Medical Physics*, Vol. 25, Issue 10, October 1998

No. 63 “Radiochromic Film Dosimetry,” AAPM Radiation Therapy Committee Task Group #55, Reprinted from *Medical Physics*, Vol. 25, Issue 11, November 1998

No. 64 “A Guide to the Teaching Of Clinical Radiological Physics To Residents in Diagnostic and Therapeutic Radiology,” Revision of AAPM Report #11, AAPM Committee on the Training of Radiologists, January 1999

No. 65 “Real-Time B-Mode Ultrasound Quality Control Test Procedures,” AAPM Ultrasound Task Group #1, Reprinted from *Medical Physics*, Vol. 25, Issue 8, August 1998

No. 66 “Intravascular Brachytherapy Physics,” AAPM Radiation Therapy Committee Task Group #60, Reprinted from *Medical Physics*, Vol. 26, Issue 2, February 1999

No. 67 “Protocol for Clinical Reference Dosimetry of High-Energy Photon and Electron Beams,” AAPM Task Group #51, Reprinted from *Medical Physics*, Vol. 26, Issue 9, September 1999

No. 68 “Permanent Prostate Seed Implant Brachytherapy,” AAPM Medicine Task Group #64, Reprinted from *Medical Physics*, Vol. 26, Issue 10, October 1999

No. 69 “Recommendations of the AAPM on $^{103}$Pd Interstitial Source Calibration and Dosimetry: Implications for Dose Specification and Prescription,” Report of the Low Energy Interstitial Brachytherapy Dosimetry Subcommittee of the Radiation Therapy Committee, In progress (2001)

No. 70 “Cardiac Catherization Equipment Performance,” Task Group #17 Diagnostic X-ray Imaging Committee, February 2001

No. 71 “A Primer for Radioimmunotherapy and Radionuclide Therapy,” Task Group #7 Nuclear Medicine Committee, April 2001

No. 72 “Basic Applications of Multileaf Collimators,” Task Group #50 Radiation Therapy Committee, July 2001

No. 73 “Medical Lasers: Quality Control, Safety, Standards, and Regulations,” Task Group #6 Joint Report of AAPM General Physics Committee and American College of Medical Physics, In progress (2001)

No. 74 Unassigned

No. 75 "Clinical Use of Electronic Portal Imaging," AAPM Task Group #58. Reprinted from *Medical Physics*, Vol. 28, Issue 5, May 2001

No. 76 "AAPM Protocol for 40–300 kV X-ray Beam Dosimetry in Radiotherapy and Radiobiology," AAPM Task Group #61. Reprinted from *Medical Physics*, Vol. 28, Issue 6, June 2001

Return to: Medical Physics Publishing
4513 Vernon Blvd.
Madison, WI 53705-4964
(800) 442-5778 phone
(608) 265-2121 FAX

Name: ____________________________________________________

Address: __________________________________________________

__________________________________________________________

__________________________________________________________

________ copies of________________________________ @________

________ copies of________________________________ @________

________ copies of________________________________ @________

Prepayment required
U.S. check or International Money Order

Amount enclosed $_____