2003

Multileaf collimator positional reproducibility evaluated with a two-dimensional diode array

Kara King Ferachi

Louisiana State University and Agricultural and Mechanical College

MULTILEAF COLLIMATOR POSITIONAL REPRODUCIBILITY EVALUATED WITH A TWO-DIMENSIONAL DIODE ARRAY

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Physics and Astronomy

by
Kara King Ferachi
B.S., Louisiana Tech University, 1998
May 2003

ACKNOWLEDGMENTS

There are several people without whose support I could not have completed this project. First, I would like to thank Dr. Thomas Kirby, my thesis committee chairman. His input and guidance proved invaluable in the development of my ideas into a successful thesis project. This thesis truly could not have been completed without him.

I would also like to thank Angela Stam for always listening to my many complaints and for encouraging me to stick it out when I wanted to give up. I would like to thank Dr. Bice for his suggestions and for helping me learn along the way. I am very grateful to all of the staff at Mary Bird Perkins Cancer Center for sharing their knowledge with me and for always helping me find the answers to my endless questions.

Finally, I would like to thank my husband Kyle for supporting me throughout my many, many years as a graduate student. He has been a sounding board for the past four years and has always encouraged me to do what makes me happy. I could not have done this without him.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

ABSTRACT

When delivering the total dose via a sequence of small fields shaped by a multileaf collimator, it is important to consider leaf positional reproducibility. A small error in the leaf position can result in large dose errors to the entire field. This is true for both dynamic multileaf collimation and step and shoot delivery. The goal of this research project is to design a method of quality assurance that is easily reproducible, sensitive to small changes in leaf position, and requires minimal time on the part of the medical physicist to carry out. This paper describes a system of measurements performed with a two-dimensional diode array that can be used in conjunction with a leaf edge function determined from radiographic film to quickly and easily test the reproducibility of the multileaf collimator position with acceptable sensitivity.

CHAPTER 1

INTRODUCTION

Radiation was first used therapeutically in the late 1800s. Radiation therapy treatment machines have evolved from very low energy x-ray machines into a variety of treatment options that include high-energy electrons, high-energy photons, and even heavier particles such as neutrons or protons. The goal of radiation therapy is to kill tumor cells while at the same time limiting the dose to normal tissues. Accomplishing this goal will enhance tumor control probability and limit the adverse side effects that result from irradiating healthy tissue. The target volume must be selected to maximize the chance of controlling the tumor. Diagnostic data from computed tomography (CT), positron emission tomography (PET), and magnetic resonance imaging (MRI) scans can be used to localize the tumor. In addition, clinical experience must be used to choose margins so that microscopic cancer cells surrounding the observable tumor volume are included.

Large doses of radiation to healthy tissues will not only make the patient more uncomfortable through the course of treatment but can also leave lasting complications, depending upon the type of tissue that is irradiated and the dose the healthy tissue receives. For example, radiation exposure to the skin will cause temporary reddening, or erythema, of the skin. More serious side effects, such as necrosis, can occur in the skin if sufficient dose is delivered. Some examples of adverse effects associated with irradiation of specific healthy tissues are shown in Table 1.1. These and other side effects associated with different types of tissues must be considered in the course of treatment planning. The radiation oncologist must therefore choose a treatment volume that will encompass the tissues of possible tumor cell involvement while minimizing the volume of normal tissue that is irradiated.

Table 1.1. Examples of tissue-specific side effects of radiation.

Tissue	Associated Adverse Effect
Brain	Neurologic deficit Loss of cognitive function
Spinal Cord	Paralysis
Lung	Radiation pneumonitis Fibrosis
Kidney	Radiation nephropathy
Stomach	Ulcer

Radiation is conformed to the tumor volume in several different ways. The most straightforward method is blocking non-involved areas from the radiation beam. The physician can outline the radiation area desired on a two-dimensional image such as a conventional x-ray or a computer generated view. The radiation beam is conformed to this area by collimators and custom blocks, which will be discussed later in this chapter. To further minimize the amount of radiation passing through healthy tissue on the way to the tumor volume, several beams may be utilized from different directions to deliver the total dose, rather than a single beam. In this way, doses from the different beams add together to maximize the dose to the tumor volume without delivering the maximum dose to the healthy tissues. These beams may be assigned different weights to further limit the amount of radiation passing through especially sensitive structures such as the spinal cord.

With the advent of computer controlled treatment machines and increased treatment planning computer capability, it has become possible to further shape the radiation distribution in three dimensions. Intensity modulated radiation therapy, or IMRT, is an example of three- dimensional beam shaping and will be discussed later in this chapter. The development of these advanced treatment techniques has helped to improve tumor control and cure rates.

The first machines used in radiation therapy produced low energy x-rays that were only capable of penetrating a few millimeters into tissue. These units are therefore useful to treat only superficial lesions. An orthovoltage therapy x-ray unit has a slightly higher energy in the 200 to 300 kilovolt range. Many institutions still use the lower energy units regularly, especially for the treatment of skin lesions (Hendee and Ibbott 1996). However, due to the low penetrating ability of the beams, it is not useful to superimpose different beams, so single beams are generally used. Beam conforming for these machines is limited to shaping (blocking) in two dimensions.

Higher energy machines capable of producing photon beams in the megavolt range were developed to overcome the limitations of the orthovoltage units. One of the early megavoltage units used in radiation therapy is the Cobalt unit. These units contain a radioactive Cobalt-60 source located inside of two stainless steel containers that are welded shut to prevent radioactive material from escaping. The source is shielded with materials such as lead or tungsten so that the beam travels in a nearly single direction out of the container when desired. The Cobalt units also contain collimators that restrict radiation not traveling in the desired direction. When the Cobalt unit is not in use the source is retracted to a fully shielded position to prevent any unintended radiation exposure. Due to the higher energy radiation compared to the orthovoltage units, beams can be combined as well as shaped to conform to tumor volumes. Cobalt units may still be found in some radiation departments but have mostly been replaced by linear accelerators.

Even higher energy radiation beams are provided by medical linear accelerators, the machine most commonly used today to deliver high doses to the tumor volume (Figure 1.1). Patients are treated by beams of electrons or x-rays that are produced by a linear accelerator. To produce these beams, electrons are accelerated to very high energies using microwaves. If an x-ray beam is desired, a target material is moved into the path of the electron beam. The electrons interact with this material and a photon beam is produced from the target. The photon beam passes through a stationary primary collimator that attenuates photons not directed in the desired cone of directions. The beam is next directed through an ionization chamber and a flattening filter. The current produced in the ionization chamber is proportional to the intensity of the radiation beam. This current is converted into monitor units. The dose to the patient is delivered by programming the linear accelerator to produce a certain number of monitor units. The purpose of the flattening filter is to differentially attenuate the beam so that a more uniform dose distribution is achieved perpendicular to the beam's central axis at ten centimeters depth.

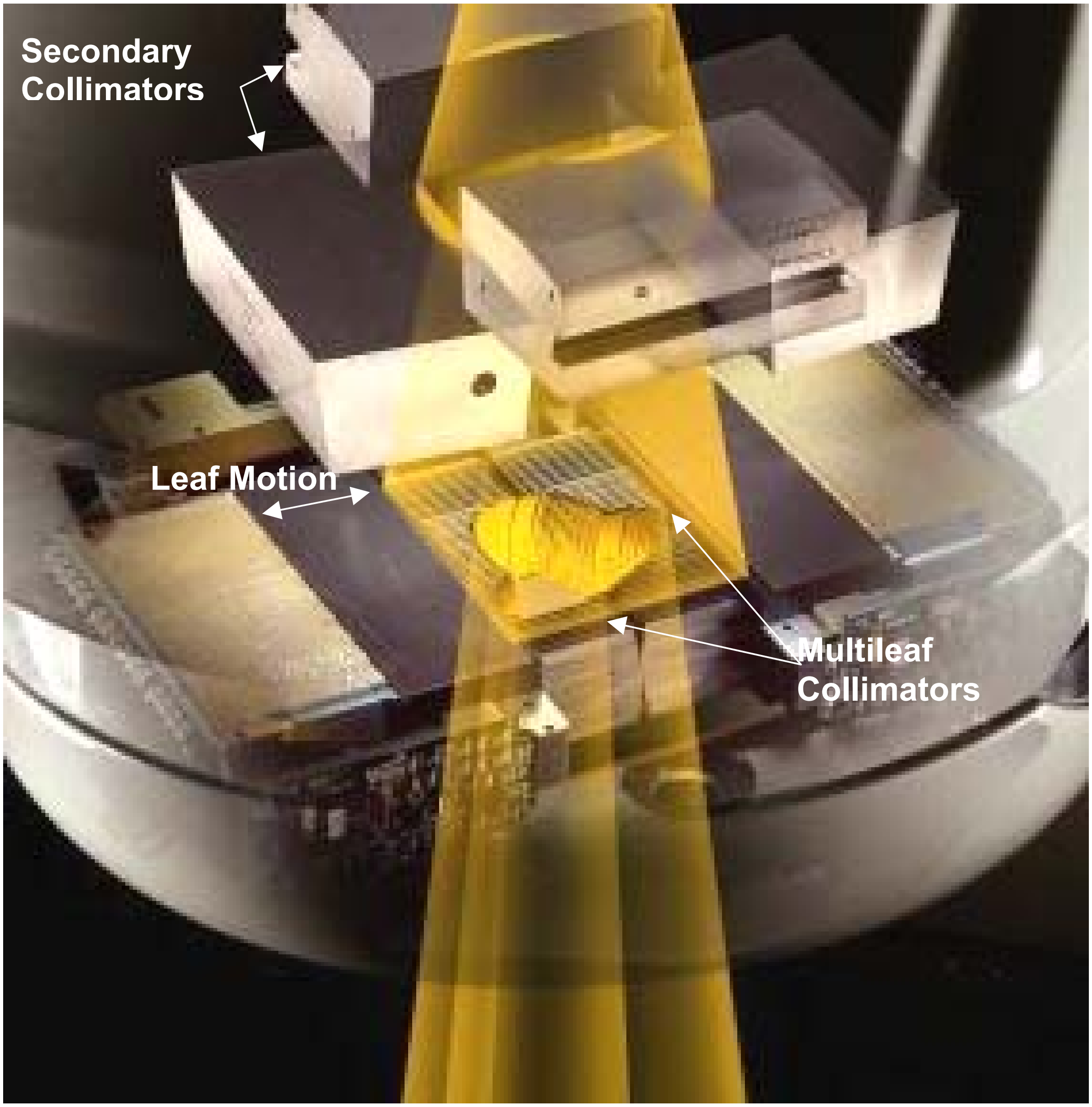


Figure 1.1. A Varian linear accelerator head. The location of the secondary collimators, the multileaf collimators and their direction of motion are all illustrated.

Shaping of the radiation beam before it reaches the patient is accomplished using several devices. The first of these is the secondary collimators. These collimators consist of jaws that are under motor control and can be moved to create a rectangular field of any size up to 40 cm by 40 cm at isocenter. The secondary collimator jaws move along an arched path to follow beam divergence and shape the beam in two dimensions. As previously mentioned, in order to minimize complications in healthy tissue, areas outside of the tumor volume should be shielded from the radiation beam. Secondary collimators are used to shape a rectangular field, but because no tumor volume is rectangular in shape, additional methods are needed to further contour the beam to the tumor volume. Additional field shaping can be done in either two or three dimensions with a tertiary collimator.

Traditional tertiary blocking or beam shaping is most commonly accomplished by custom-made cerrobend blocks. Cerrobend, a high-density material with a low melting point, may be melted and poured into a custom-made mold. The shape of the mold is specific to each beam used to treat each patient. Once the Cerrobend hardens, the custom block is used as a tertiary collimator mounted outside the head of the accelerator in the path of the beam to shape the field before it reaches the patient.

Cerrobend blocks are an effective way to shape the radiation beam, but require a time consuming manufacturing process. Another tertiary collimator that almost completely eliminates the need for custom blocks and therefore reduces production time is the multileaf collimator (MLC). A MLC is made up of many opposed pairs of small leaves mounted into two carriages on either side of the field. The leaves may be extended under motor control to shape a field that is conformal to the tumor volume. The location of the MLC on the accelerator head depends upon the accelerator manufacturer. Some manufacturers replace one pair of secondary collimator jaws with leaves, in which case the MLC is not a tertiary collimator. “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” (Boyer et al 2001). Tighter tolerances for leaf travel are required closer to the target because the further away the leaf is from isocenter, a small error in leaf positioning will translate to a larger distance at isocenter. The smaller leaf size in multileaf collimators that replace the secondary jaws can also be an advantage because the leaves do not need to be as long and therefore decrease the size and bulk of the treatment head. Manufacturers that design the MLC as a tertiary collimator mount the MLC leaf banks just below the secondary collimator jaws, as shown in Figure 1.1. A disadvantage of this method is that it increases the bulk of the treatment head. Also, the amount of clearance between the treatment head and the patient may be decreased if custom blocks or wedges are used along with multileaf collimation (Boyer et al. 2001).

In addition to varying positions of the MLC, multileaf collimators also vary in their direction of leaf motion and leaf shape according to the MLC manufacturer. Some manufacturers use a “focused” MLC in which the leaf carriages travel in an arch to follow beam divergence. In other machines, the leaves move only in a plane perpendicular to the treatment beam. This is a “nonfocused” multileaf collimator that does not follow beam divergence. The leaf edges for this type of MLC must be rounded in order to produce an acceptable penumbra. Sun and Zhu define the penumbra as “the region at the edge of a radiation beam over which the dose changes rapidly as a function of distance from the beam axis” (1995). The penumbra is described mathematically by an edge function. Edge functions and penumbra will be discussed in greater detail in chapter three.

There are two ways to describe the edge of the leaf. First is the physical edge of a leaf which is measured by the shadow of the light field. Second is the radiographic edge of the leaf, which is considered to be the point in the radiation field that is fifty percent of the intensity of an open field. In this project, all references to the leaf edge correspond to the radiographic edge, not the physical edge. It is possible with a rounded leaf edge that the penumbra is wider than that of a focused leaf. There is also some concern that the penumbra of a rounded leaf edge can change with distance off axis (Boyer et al. 2001). In addition, the edge of the light field does necessarily agree with the radiation beam edge for a rounded leaf end at off-axis locations. The sides of each leaf have a tongue and groove design in order to minimize inter-leaf leakage. Figure 1.2 shows a single leaf from a multileaf collimator, illustrating the rounded leaf edge and the tongue and groove design of the sides of the leaf.

Another application of the tertiary collimator is three-dimensional beam shaping. Three-dimensional shaping of the radiation beam results in a modulated intensity throughout the treatment field. This treatment technique is called intensity modulated radiation therapy (IMRT). IMRT treatments provide a better fit to the tumor volume than previous conformal radiation therapy. Figure 1.3 shows a comparison of the fit of the dose delivered with an IMRT plan to that delivered with a conventional conformal therapy plan. IMRT treatment plans are created with an inverse planning technique. In inverse planning, the physician is able to specify the dose to be delivered to the tumor volume and may also enter the dose limits to the healthy structures surrounding the tumor volume. These values are entered into a treatment-planning computer, which then creates a plan that matches the specified parameters as closely as possible. The IMRT plan is delivered as a combination of fields entering the patient from different angles. Either compensators or multileaf collimators are used to modulate the intensity of each beam.

Compensators are made by varying the thickness of a particular material to partially attenuate the beam before it reaches the tumor volume. The material used in the compensator varies depending on the amount of attenuation required. The compensator material covers the entire field and is mounted to the outside of the treatment head. Compensators are usually used in conjunction with custom blocks for additional beam shaping.

To create intensity modulated fields with a MLC the leaves are moved to shape very small field sizes. Varying amounts of monitor units determined by an inverse planning algorithm are delivered to these small fields to closely fit the dose only to the tumor volume. Two different methods are used to deliver intensity-modulated fields with a multileaf collimator: dynamic multileaf collimation and step and shoot delivery. In dynamic multileaf collimation, the leaves are in constant motion throughout the beam delivery. In step and shoot delivery, the beam delivery is paused while the leaves are repositioned.

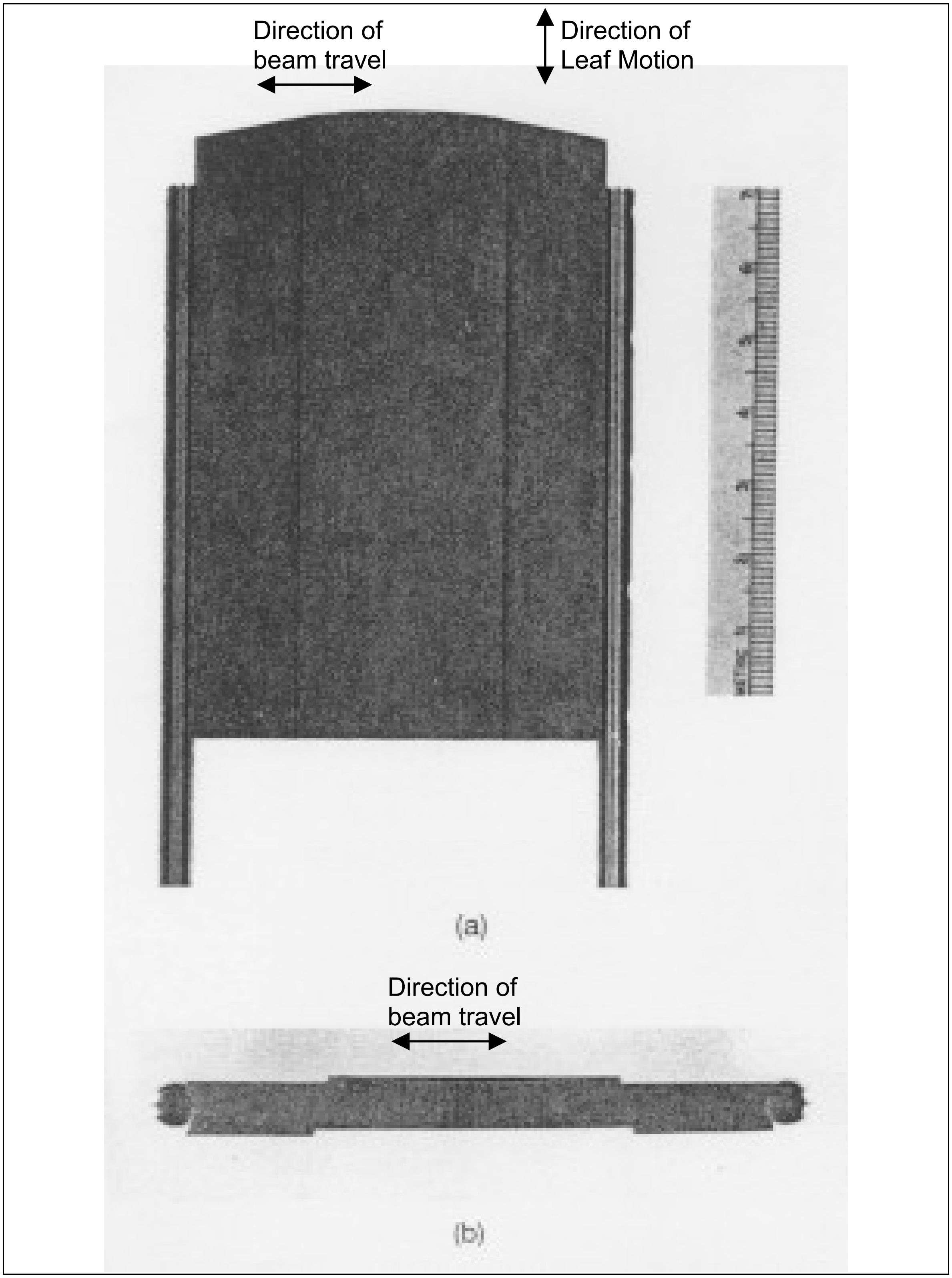
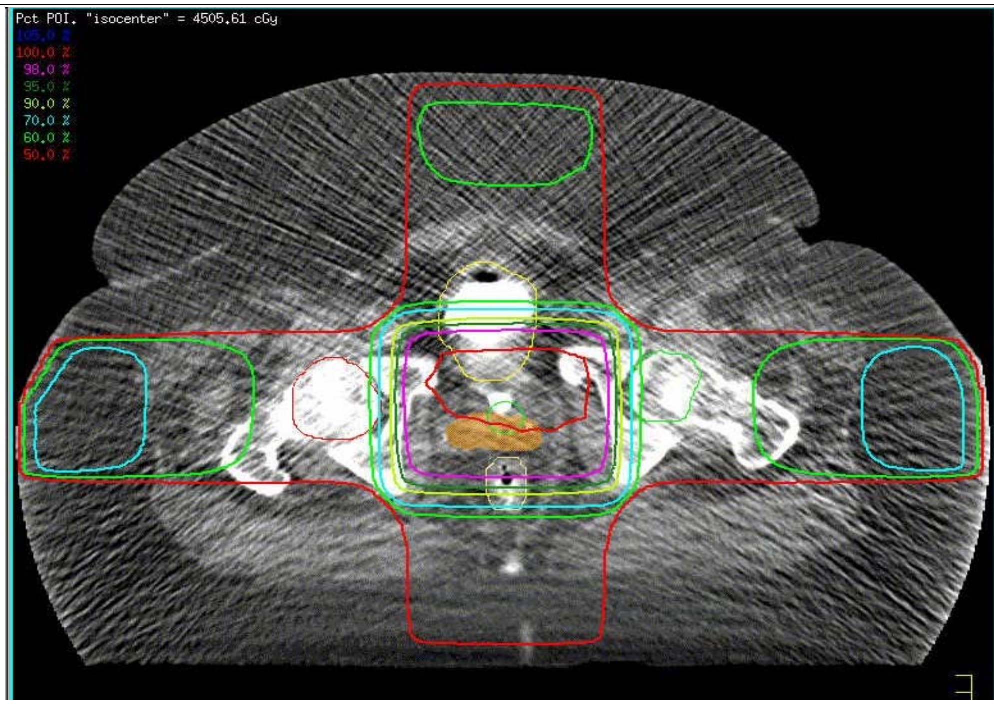
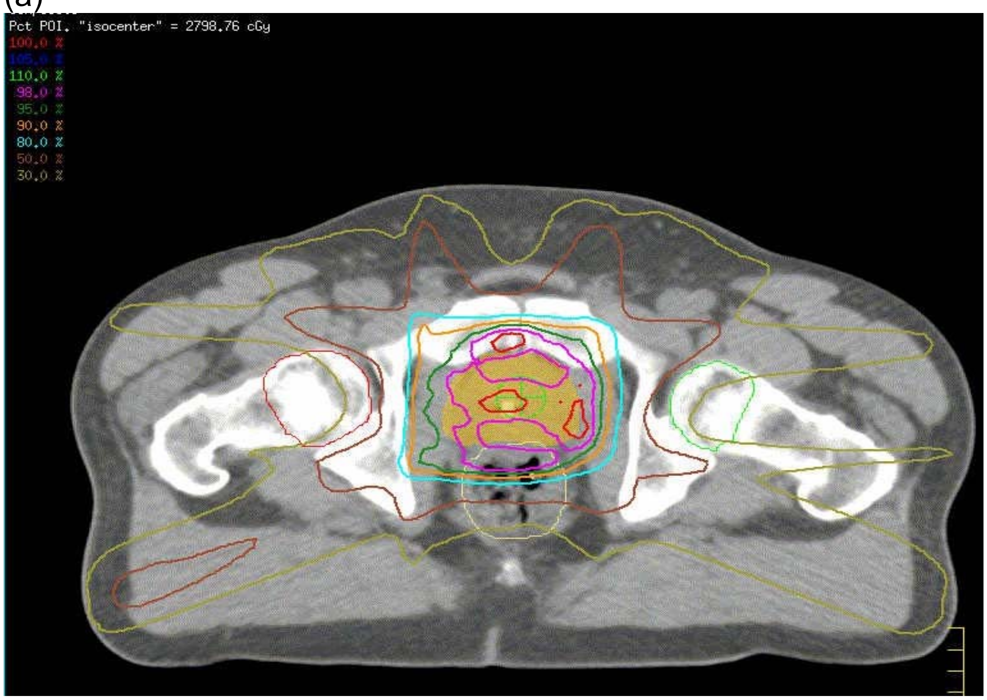


Figure 1.2. A single leaf from a multileaf collimator. This picture shows in detail (a) the rounded leaf edge and (b) the tongue and groove design of the sides of the leaves, as well as indicating the direction of beam travel with respect to the leaf.



(a)



(b)

Figure 1.3. Comparison of IMRT and conventional 3-D radiation therapy. The plan shown in (a) is a conventional three-dimensional radiation therapy prostate treatment plan and (b) is an IMRT prostate treatment plan.

When delivering the total dose via a sequence of small fields shaped by a multileaf collimator, it is important to consider leaf positional reproducibility. As will be discussed in detail in the next chapter, a small error in the leaf position can result in large dose errors to the entire field. This is true for both dynamic multileaf collimation and step and shoot delivery. This research project will attempt to design a method of quality assurance that is easily reproducible, sensitive to small changes in leaf position, and requires minimal time on the part of the medical physicist to carry out. This project describes a system of measurements performed with a two-dimensional diode array that can be used in conjunction with a leaf edge function to quickly and easily test the reproducibility of the multileaf collimator position with acceptable sensitivity.

CHAPTER 2

REVIEW OF LITERATURE

The introduction of multileaf collimators into radiation oncology has provided many advantages, while at the same time introducing new challenges. Multileaf collimators, when used as a replacement for conventional blocks, reduce the time required by eliminating the block production process, as well as reducing the time required for the radiation therapist to set up between sequential fields (Jordan and Williams 1994). However, with advances in technology such as intensity modulated radiation therapy (IMRT), the leaves of a multileaf collimator may be utilized in a manner beyond what was originally intended (LoSasso, Chui, and Ling 2001). Additional quality assurance methods are therefore needed to ensure normal leaf function and accurate leaf position.

There are several possible causes of error in leaf position addressed in the literature. LoSasso et al. found that leaf positional inaccuracy "appears to be related to the amount of usage of individual leaf motors". LoSasso et al. found that after IMRT was initiated at their facility, leaf motors had to be replaced more often. The leaves at the center of the multileaf collimator were found to be the most susceptible to motor failure. These center leaves are used for prostate IMRT treatments at their institution (2001). LoSasso, Chui, and Ling also cite loss of counts in the primary leaf position encoders as a source of leaf position error. They state, "On occasion that the chronic loss of counts of a primary encoder becomes excessive, leaf position errors could exceed 0.5 mm at isocenter. Reinitializing the MLC will temporarily alleviate the problem, but position errors may go unnoticed because an interlock will not be activated until the error reaches 2 mm". LoSasso, Chui, and Ling recommend a semi-weekly test to check for these types of encoder errors (2001). Two other sources of uncertainty according to Budgell et al. are "the precision of the MLC control system" and "the absolute accuracy of calibration of the MLC leaf positions". Budgell et al. assert, "If leaves are calibrated within ±1 mm, an MLC controller precision of 0.1 mm can only guarantee an absolute positional accuracy of ±1.1 mm" (2000). According to LoSasso, Chui, and Ling, a "1 mm error in the calibrations of the jaws and leaves can be tolerated" when the multileaf collimator is being used only to shape a static field. In IMRT treatments "leaf movements need to be executed much more precisely. Therefore, a much tighter tolerance of ~0.2 mm" is necessary (2001).

The American Association of Physicists in Medicine Task Group No. 50 describe calibration of the leaf position for a Varian multileaf collimator in the following way:

> 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 … to calibrate the leaf position. The calibration values are saved in a table for use by the control system. (Boyer et al. 2001)

This calibration procedure is a very important step to ensure leaf positional accuracy. According to Boyer et al., "periodic checking and recalibration are also needed to ensure the integrity of the controlling system" (2001).

Several researchers have documented the importance of quality assurance of multileaf collimator leaf stability. Budgell et al. state that in dynamic multileaf collimation used for IMRT, a 1 cm slit traveling across a distance of 10 cm can have up to a 10% change in dose for a 1mm change in the width of the slit due to leaf position inaccuracy in dynamic multileaf collimation. According to Budgell et al., “leaf position errors will normally not cause dosimetric errors in step and shoot deliveries except for very thin fields for which output factor is strongly dependent on field width” (2000). Low et al. state that accuracy in leaf positioning for step and shoot deliveries is very important in regions where there are multiple sub field abutments. Low et al. also state, “errors in leaf positioning will cause corresponding errors in the delivered dose in the abutment region, with the dose errors proportional to the penumbra slope at the edge of each sub field.” Low et al. concluded that errors in the abutment regions of sub fields could cause 16.7% dose errors for 6 MV photons for each millimeter of error (2001).

According to Chui, Spirou, and LoSasso, “positional inaccuracy of the leaves may affect the dose distribution everywhere within the field” (1996). This is a major difference from conventional blocking with multileaf collimators. In traditional blocking, the leaves are set to a single position throughout the entire treatment, so an error in leaf position will affect only the area just inside the block. With dynamic multileaf collimation, an error in a single leaf’s position can be carried across the entire field, leading to hot spots if the leaf is lagging behind or cold spots if the leaf is in front of its intended position (Chui, Spirou, and LoSasso 1996). Hot and cold spots can also result in step and shoot deliveries in the areas of multiple sub-field abutments. These findings emphasize the importance of assuring leaf positional accuracy when the multileaf collimator is being used clinically for IMRT in either the dynamic or step and shoot mode.

Many different quality assurance procedures have been proposed in the literature. LoSasso, Chui, and Ling recommend a semi-weekly test using Kodak V2 Ready Pack film to verify leaf positions at the end of the treatment day. This test exposes the film to “a DMLC field that produces a matrix of high intensity regions, 1 mm wide and spaced 2 cm apart”. If any leaf position is off by more than 0.2 mm, that leaf’s motor must be replaced. The physicist evaluates the film visually without having to digitize it. This decreases the time required for evaluation, an important point for any QA process (2001). LoSasso, Chui, and Ling also introduced a quality assurance method that uses a cylindrical ion chamber to measure the dose “for a uniform field delivered dynamically with a small, 0.5-cm-wide, sweeping gap”, which is normalized to a static 10 x 10 cm^2 field created by collimator jaws. The authors state that this method is “capable of detecting less than 0.1 mm deviation” in the leaf position (1998).

Budgell et al. created a test to measure daily variation in leaf position using a 1 cm slit formed only with the leaves. This slit moves across a distance of 10 cm. Budgell et al. found that “a 1 mm change in slit width leads to a 10% change in dose” making this test very sensitive to inaccuracies in position. The doses were measured with an ionization chamber and normalized to a 10 cm x 10 cm static field (2000). Another test was devised by Chui, Spirou, and LoSasso to be used as a routine quality assurance check. In this test, “the paths of the left and right leaves were intentionally offset by 1 mm to produce hot spots on the resultant intensity profile". If the leaves are traveling to their intended positions, lines of increased intensity will be shown on film at equally spaced intervals. The widths of these hot spots are easily determined by visual inspection. This provides a quick and easy way to identify leaf positional inaccuracies on a daily basis (1996).

LoSasso, Chui, and Ling have also tested accuracy of leaf position with gantry angle. LoSasso, Chui, and Ling performed the previously mentioned 0.5 cm wide sweeping gap test at gantry angles of 0, 90, 180, and 270 degrees "to assess the effect of gravity on the performance of the multileaf collimator in dynamic mode." The dose delivered was measured with a cylindrical ion chamber at isocenter and was found to be independent of gantry angle (1998). In a separate quality assurance test, LoSasso, Chui, and Ling used the Sun Nuclear Corporation Profiler, a diode array, to measure relative dynamic multileaf collimator output at gantry angles at 90 and 270 degrees. They found that "small variations were observed on the central axis, consistent with the ion chamber measurements, but larger variations exist at off-axis points" (2001). Chui, Spirou, and LoSasso state that their previously mentioned quality assurance test that produces high intensity lines at equally spaced intervals can be performed with the gantry angle at ninety degrees with the collimator turned so that "the leaves move perpendicular to the floor to maximize the gravity effect" to test the effect of gravity on leaf positional accuracy (1996).

Most of the quality assurance procedures discussed in the literature involve using radiographic film and/or ion chambers. Other research has been carried out to determine the usefulness of diode arrays compared to film and ion chamber measurements. According to Paul Jursinic, the biggest advantage of using diodes is the immediate availability of the results. Jursinic also states, “other advantages of diodes include high sensitivity, good spatial resolution, small size, simple instrumentation…ruggedness, and independence from changes in air pressure” (2001). According to Essers and Munheer, another advantage of diodes is “the sensitivity per unit volume of a diode is about 18,000 times higher than for an air-filled ionization chamber” (1999). To evaluate the intensity profile produced using dynamic multileaf collimation, Papatheodorou et al. used radiographic film, point measurements from a cylindrical ion chamber, and the SNC Profiler 1170 linear diode array. Papatheodorou et al. found very good agreement between the profiles measured by the Profiler and the ion chamber. They concluded that the diode array is “a very useful tool for measuring intensity profiles with the condition that the relative sensitivity of diodes is carefully corrected” (2000). Zhu et al. also evaluated the SNC Profiler as a tool for measuring the profiles of enhanced dynamic wedge dosimetry. Zhu et al. found the diode array to be about twenty times faster than an ion chamber for quality assurance purposes, with very good agreement between the measured profiles. Zhu et al. concluded that a diode array, specifically the Profiler, “provides good spatial resolution and is useful for commissioning a dynamic wedge” (1997). Hansen et al. used the Schuster BMS-96 diode array to measure beam profiles of small radiation segments. The diode array was used because the dose was delivered by 10 MU and that is not enough time for a scan across the beam that is used during the standard calibration procedure. According to Hansen et al., “This device is ideal for profile measurements of any segment size, and can measure profiles for field sizes up to 40 cm" (1998).

Although much research has been done on multileaf positioning, most of the work was done with cylindrical ion chambers, film, or a linear diode array. The diode arrays were shown to be less time consuming than film or point measurements from an ion chamber and the profiles measured with the diode array were in good agreement with the film and ion chamber measurements. A two-dimensional diode array should be able to provide more information over an entire field, in a more efficient manner than film or an ion chamber, about the multileaf performance at a variety of off-axis points. By mounting the diode array to the gantry, the diode array can also be used to test multileaf positional reproducibility at any gantry angle.

CHAPTER 3

MATERIALS AND METHODS

3.1 Description of the Multileaf Collimator

The multileaf collimator used for this research was a Varian Medical Systems Millennium MLC-120, mounted below the secondary collimators on a Varian Clinac 21 EX linear accelerator. The bottom of the multileaf collimator is 53.5 cm from the linear accelerator target, which corresponds to a distance of 46.5 cm from isocenter. The isocenter of the machine "is the point of intersection of the collimator axis and the gantry axis of rotation" (Khan 1994). The isocenter for the 21 EX is at a distance of 100 cm from the source. The total field size of the multileaf collimator is 40 cm x 40 cm, shaped by 120 individual leaves. This multileaf collimator has two different leaf widths. The central 20 cm of the field is shaped by leaves with a 0.5 cm projected width at isocenter and the leaves that shape the outer 20 cm of the field project a 1.0 cm width at isocenter. The leaves are mounted within two carriages and each leaf can move to a maximum extension of 15 cm at isocenter from the carriage. The individual leaves have a rounded edge and the sides of the leaves have a tongue and groove arrangement to minimize leakage as illustrated in chapter one.

3.2 Description of the Diode Array

The diode array used in this research was a prototype version of the MapCheck^{TM} two-dimensional therapy beam measurement system made by Sun Nuclear Corporation of Melbourne, Florida. The prototype contains a 10 cm x 10 cm array of 221 diodes. The active detector area of the diodes is 0.8 mm x 0.8

mm. The diodes are spaced 1 cm apart on each row and each row is spaced 5 mm apart, as shown in Figure 3.1. The inherent buildup on top of the diodes is about 1.32 g/cm^2. The physical distance of this buildup is 1.13 cm.

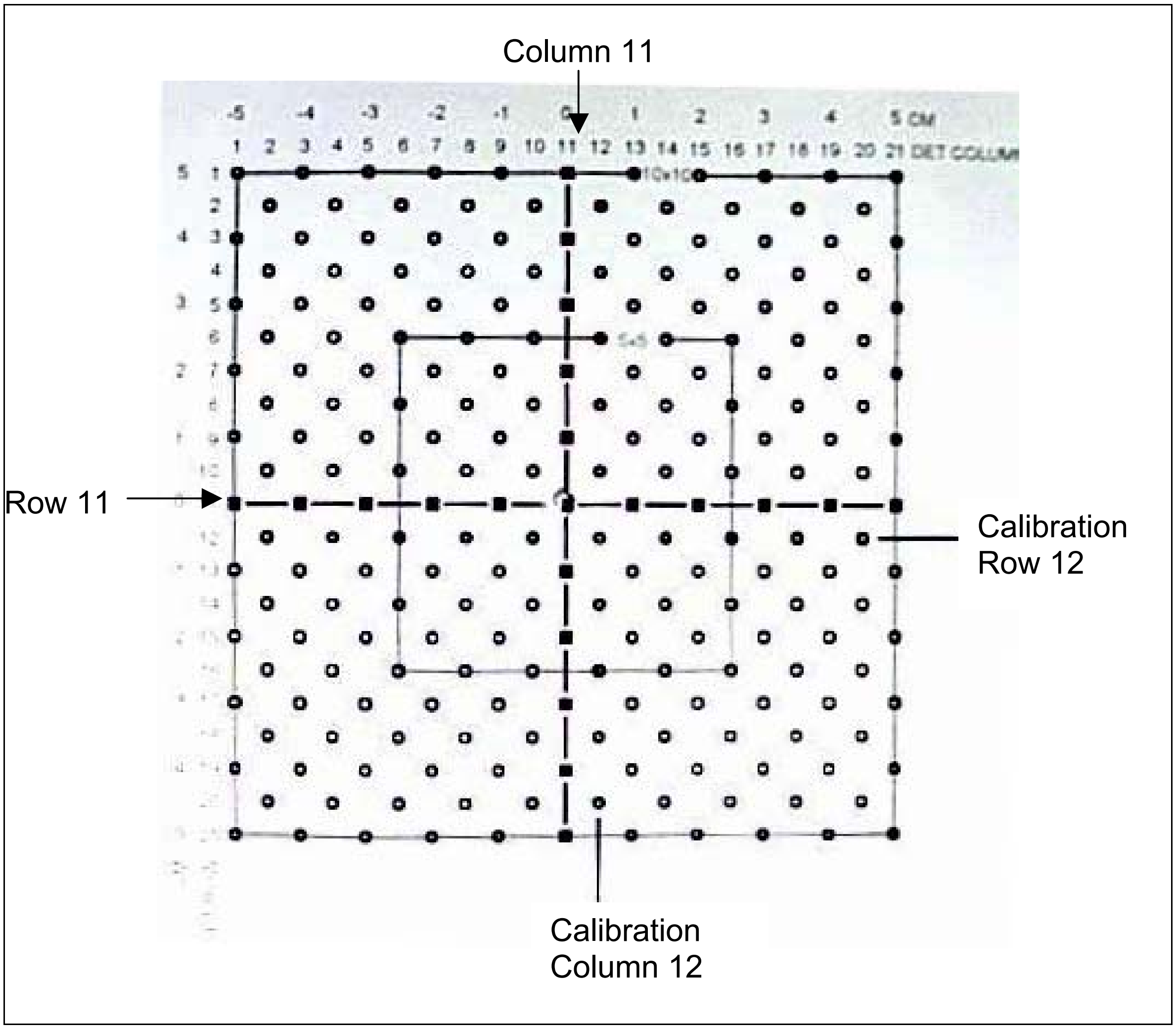


Figure 3.1. The Sun Nuclear Corporation prototype diode array. Row 11 and column 11 are the central axis of the diode array. Row 12 and column 12 are the locations used for calibrating the array and are marked "CAL" on the face of the array.

The prototype diode array comes with its own software. The diode array was connected to a personal computer using the same data port that is used for the Profiler also made by Sun Nuclear Corporation. Each time the software was started, a background measurement had to be acquired and the diode array had to either be calibrated or a previous calibration file must be loaded. To calibrate, the central axis of the diode array (row 11, column 11) was first aligned with the machine crosshairs. The diode array was placed on top of the couch at a source to surface distance of 100 cm. The field size is set to 15 cm by 15 cm using the secondary collimator jaws. Three separate doses of 200 cGy were delivered, with the diode array rotated clockwise 90 degrees between the three 200 cGy dose deliveries. The machine crosshairs were then aligned with the row and column marked “cal” (row 12, column 12) on the diode array and another 200 cGy dose was delivered. The calibration file was then saved so that it could be used in future acquisitions without having to recalibrate the diode array. Once background was acquired and a calibration file was loaded, the diode array was ready to acquire data. The results from all measurements included raw counts as well as corrected counts and were saved as both binary and ASCII files. The acquired data were easily adaptable into a spreadsheet program.

3.3 Diode Array Output Variability

To determine the variation in the response of the diode array between sequential readings, ten separate readings under identical conditions were taken. The diode array was placed at the central axis with a source to surface distance of 100 cm. The multileaf collimators were retracted and the secondary collimators were set to a 15 cm x 15 cm open field. Thirty monitor units of 10 MV photons were delivered ten times in succession with the output recorded between each delivery. There was no change in the setup of the diode array between readings.

3.4 Description of an Edge Function

A collimator placed into a beam of radiation will attenuate the portion of the beam that passes through it. However, at the edge of the collimator, the region at the edge of the beam will have a rapidly changing dose with distance from the edge. This is the penumbra of the beam discussed in the introduction. The penumbra occurs for two reasons. First, because the radiation source, i.e. the linear accelerator target, has some finite size. Therefore, the photons produced to one side of the target will pass the collimator at some angle and not be absorbed. These photons cause the amount of radiation just underneath the collimator edge to be some value between fifty percent of the maximum value within the open field and zero. The second reason for the penumbra is photons that are partially attenuated but still transmit through the very edge of the collimator. According to Sun and Zhu, the amount of radiation transmitted is dependent upon “field size, the distance from the x-ray source, and the collimator edge” (1995). The mathematical relation that describes the shape of the edge of the radiation beam as it rapidly changes from some maximum value within the field to near zero underneath the collimator is called an edge function. The shape of an edge function varies among different collimators depending upon their shape and whether the direction of travel is in line with beam divergence. Figure 3.2 shows a typical edge function produced by a collimator edge.

3.5 Determining the Edge Function of a Single Leaf

Two separate methods, one using radiographic film and the other using the diode array, were used to experimentally determine the edge function of a single leaf. The film edge function was measured by a single exposure of 30 cGy to the film with a single leaf extended. The diode array edge function was determined by moving the leaf across a single diode in 1 mm increments through a total distance of 4.8 cm.

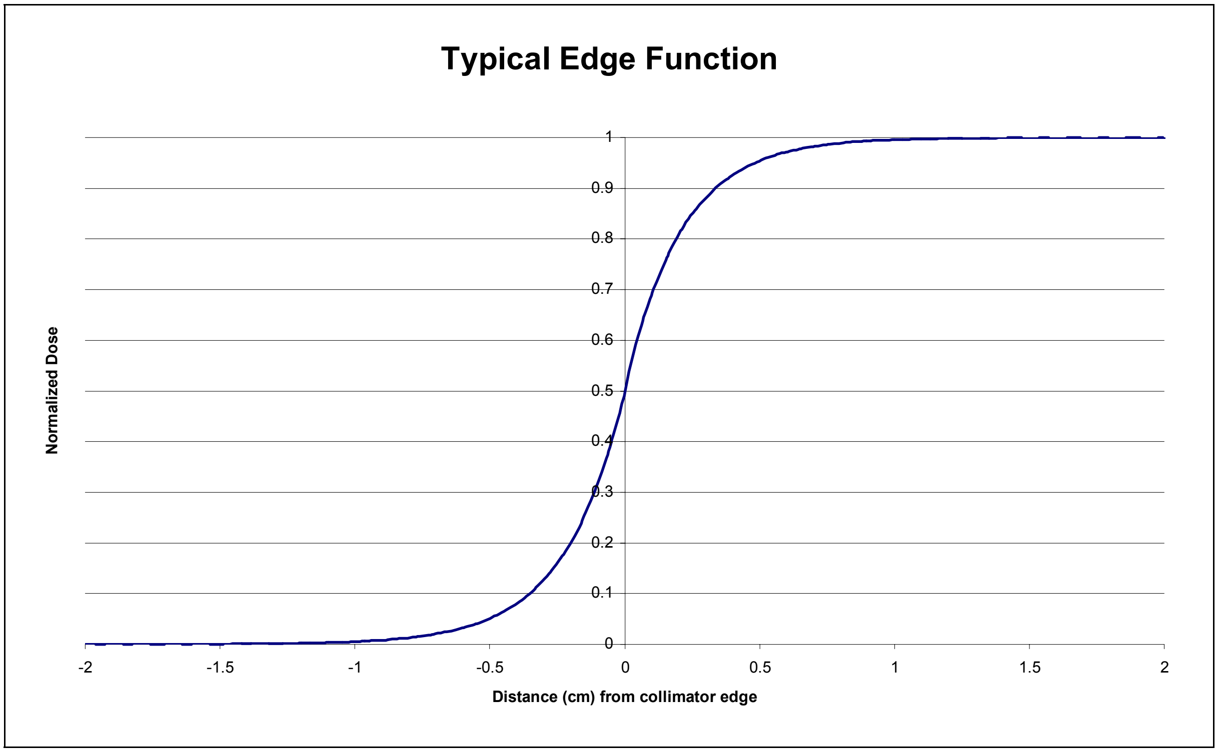


Figure 3.2. A typical edge function from a collimator edge. The edge function ranges from a value of 1.0 at a position inside of the field to a value of zero outside of the field (underneath the collimator).

To determine the edge function with film, radiographic film (X-Omat V, Eastman Kodak Company, Rochester, NY) was placed in a water-equivalent phantom at the depth of maximum dose for 10 MV, with a source to surface distance of 100 cm. In this case the thickness of water-equivalent material covering the film was 2.5 cm. The secondary collimators were set to a 15 cm x 15 cm field size. The leaves of the multileaf collimator were also set to a 15 cm x 15 cm field size, with a single leaf along the central axis extended to its zero position.

The zero position of a leaf is located at the central axis of the machine. With the single multileaf extended, the film was exposed to 30 monitor units of 10 MV photons, or approximately 30 cGy.

Using a Vidar Systems Corporation VXR-12 plus film digitizer, the film was entered into the RIT113 Film Dosimetry System (Radiological Imaging Technology, Colorado Springs, CO) for analysis. The film was digitized with a resolution of 169 microns. To determine the edge function of the single extended leaf, a profile was taken at the center of the image of the extended leaf using the orthogonal profiles function in the RIT113 system and converted into an ASCII file. Only the profile running parallel to the leaf was used to determine the edge function. The ASCII data from the profile were then imported into a spreadsheet program. The data were first normalized to the maximum value on the central axis and then fitted to two functions using the following algorithm:

Eq. 3.1 Inner: $P_i(x,y,z)=1 - 0.5 \times e^{(-ain \ \times \ dis(x,y) / p(z))}$

Eq. 3.2 Outer: $P_o(x,y,z)=T_0 + (0.5 - T_0) \times e^{(-aout \ \times \ dis(x,y) / p(z))}$

where:

Inner = the edge function described by the portion of the data in the open part of the field,

Outer = the edge function described by the data covered by the leaf,

dis(x,y) = Distance of the point from the leaf edge,

T_0 = jaw transmission factor (normalized to zero in this project),

a_{in} and a_{out} = fitting parameters determined from the measured data,

p(z) = (SAD-SJD-z)/SAD-SJD). This is a dis(x,y) correction factor for penumbral fit, p(z)=1 on the isocentric plane,

SAD = Distance from linear accelerator x-ray source to isocenter,

SJD = Distance from the source to the bottom of the multileaf collimator jaw edge along the beam axis.

These two functions represent the best fit to the measured edge function data. These algorithms are from the X-Knife® version 4.0 User's Manual published by Radionics Software Applications, Inc. Once the fitting parameters were determined from the measured data, the x, y position of any leaf could then be determined by entering the percentage into the inverse of the function. It is important to note that all of the edge functions were varied in one dimension only for this project. Edge functions were fitted using equations 3.1 and 3.2 for each of the six leaves studied in positions both on and off the central axis.

To determine the edge function parameters with the diode array, the array was placed at a source to surface distance of 100 cm. The field size was set to 15 cm by 15 cm using both the secondary jaws and the multileaf collimator. The diode array was lined up so that the single extended multileaf would pass directly over the central row of diodes. This position was approximately 2.5 mm offset from the central axis. The single multileaf was programmed to stop approximately every millimeter from 2.4 cm left of the center to 2.4 cm right of the center. At every stop, 30 monitor units of 10 MV photons were delivered to the diode array and the output was recorded. The edge function was constructed by normalizing the data to an open field reading, then charting the reading of the central diode at every stop of the multileaf. An edge function was measured with the diode array only for leaf 30B for comparison to the edge function determined from the film data. Figure 3.3 illustrates the effect on the edge function of moving a single leaf while the diode remains stationary. The diode is able to remain stationary and measure leaf displacement because as the leaf moves, the edge function moves along with the leaf. Therefore, the diode array is measuring a different location on the edge function curve as the leaf moves over it.

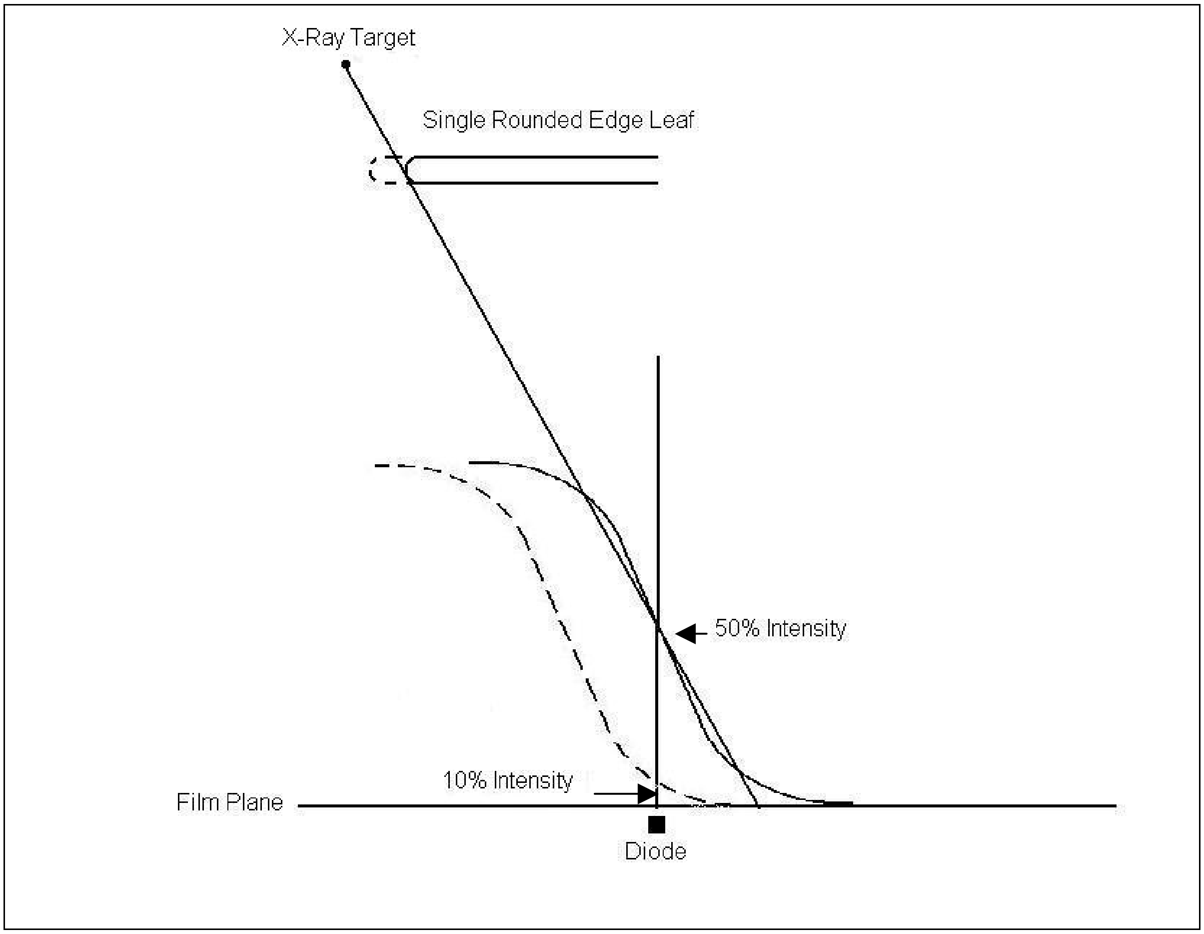


Figure 3.3. Effect of leaf displacement on diode readings. The curves represent the beam intensity near the edge of the field (edge functions). The diode is positioned at the original beam edge (solid lines) and reads 50% of the signal received in the open field. When the leaf is displaced slightly (dashed lines), the edge function follows the projection of the leaf edge. The diode, which remains stationary, consequently yields a different reading corresponding to the edge function value at the diode position. The diode reading can therefore be used in conjunction with the edge function to measure leaf displacement.

3.6 Testing Multileaf Positional Reproducibility on the Central Axis

The reproducibility of the position of a single multileaf was tested under several different conditions. The different tests alter the extension of a single leaf from the rest of the leaves in the multileaf collimator carriage containing the extended leaf to determine whether this has an effect on the reproducibility of the position of the multileaf between data acquisitions. All of these tests were performed with the diode array at a 100 cm source to surface distance.

Three different leaf extensions were tested for each of six different leaves, three leaves from each carriage. The distances of the leaves tested from the central axis are shown in Table 3.1. The locations of these leaves are illustrated in Figure 3.4. For each test, the secondary collimators were set to a 15 cm x 15 cm field size. The gantry angle and the collimator angle were both 180 degrees. For each leaf, the leaf position that corresponded to an approximately fifty percent response from the central diode in the array relative to an open field was determined experimentally. This fifty percent position was then used in each of the tests. These positions are shown for each leaf in Table 3.2. The same diode in the array was used to test each leaf. Only one diode was used in order to eliminate another variable that would be introduced into the experiment if different diodes were used for each test. The diode array was moved to a different position for each leaf so the central diode was at the center of each leaf being tested.

3.6.1 2.0 cm Leaf Extension

The first reproducibility test was performed with the secondary collimators set to a 15 cm x 15 cm field. This test extended the leaf 2.0 cm from the rest of the leaves in the carriage. The single extended leaf was set to its experimentally determined fifty percent position. The opposite carriage not containing the leaf to be extended is fixed at 7.5 cm. Twenty-five measurements were taken, retracting and re-extending the multileaf collimator between measurements. An illustration of this field for leaf 30 on carriage B is shown in Figure 3.5(a).

Table 3.1. Location of leaves tested relative to the central axis.

Leaf Number	Leaf Width	Leaf Location
6	1.0 cm	14 cm to 15 cm from central axis
19	0.5 cm	5.5 cm to 6 cm from central axis
30	0.5 cm	0 cm to 0.5 cm from central axis

Table 3.2. Approximate fifty percent positions.

Leaf	Position	Diode Response Relative to Open Field Response
6A	0.12 cm to left of central axis	53.1%
6B	On central axis	52.3%
19A	0.12 cm to left of central axis	49.7%
19B	0.11 cm to right of central axis	45.4%
30A	0.12 cm to left of central axis	47.9%
30B	0.11 cm to right of central axis	46.2%

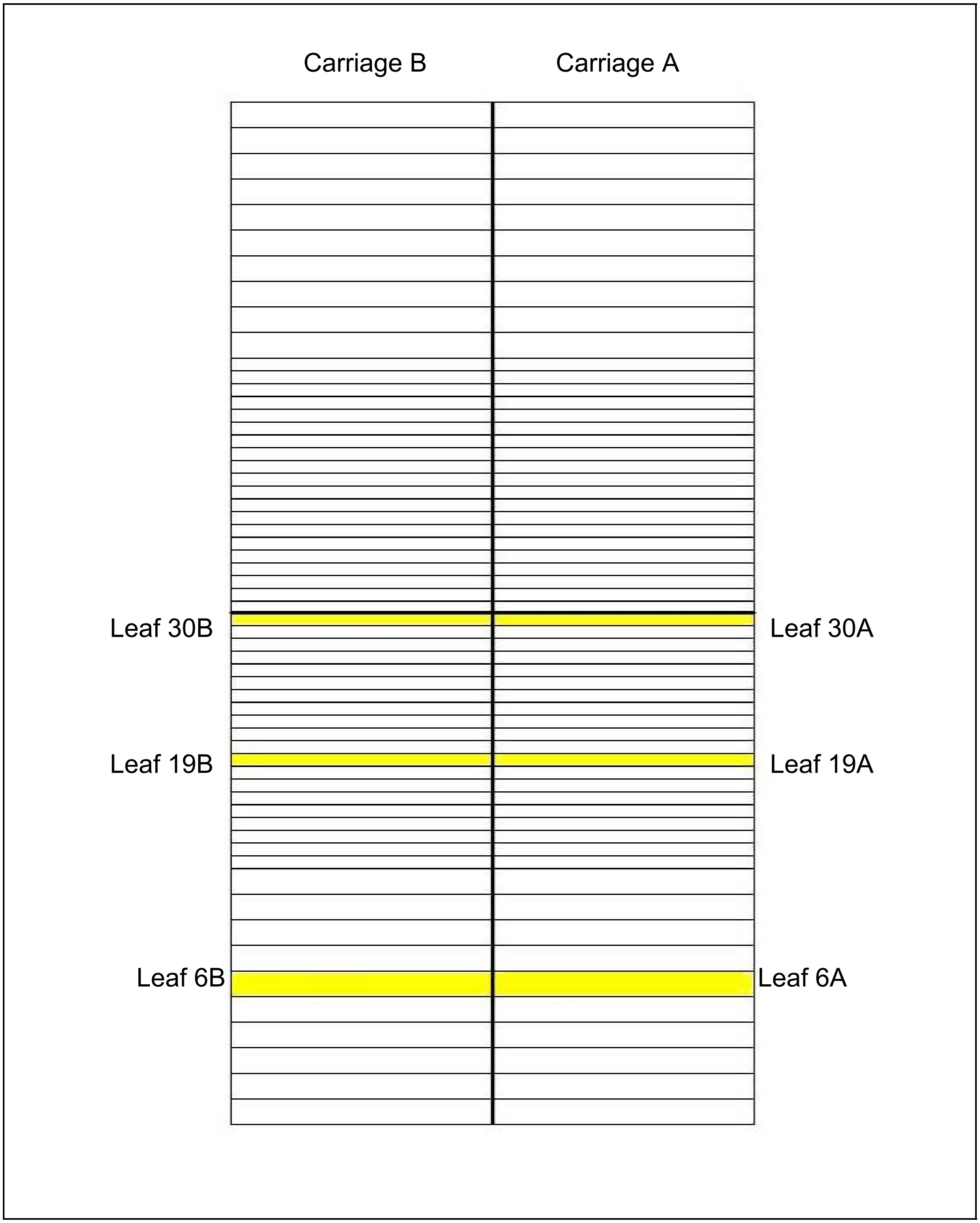


Figure 3.4. An illustration of the locations of the leaves tested within the multileaf collimator. The dark line represents the central axis of the machine. The highlighted leaves are the six leaves that were tested.

3.6.2 7.5 cm Leaf Extension

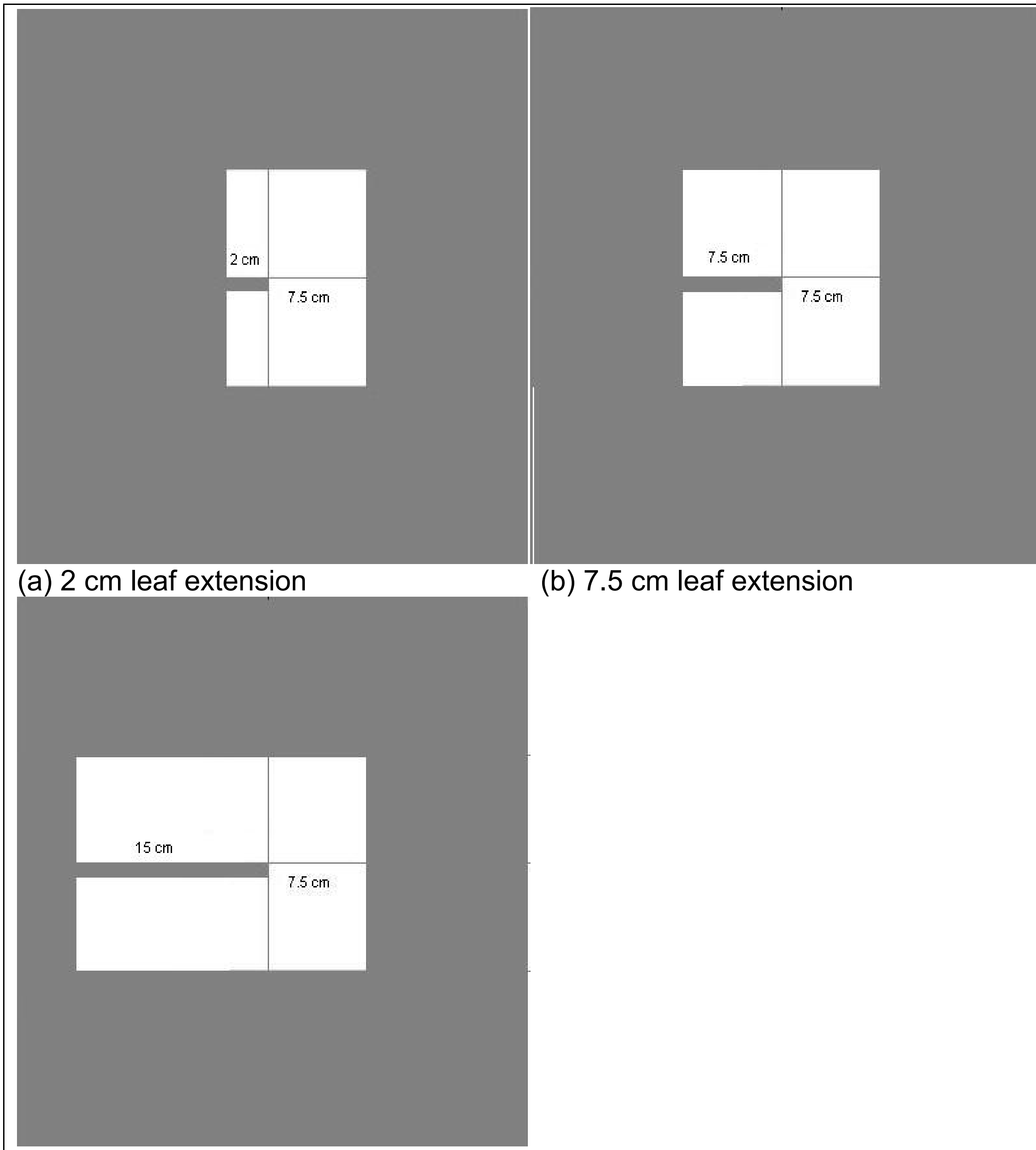
The multileaf collimator was programmed to form a 15 cm by 15 cm box, with a single leaf extended to the center of the field in the fifty percent position discussed previously. The edge of the extended leaf was 7.5 cm from the edges of the rest of leaves in the carriage. The carriage not containing the extended leaf was set to a distance of 7.5 cm from the edge of the extended leaf, the same distance as for the previous experiment. Twenty-five separate measurements were then taken with the leaf in this position. Between each acquisition the multileaf collimator was retracted and then returned to the extended position. An image of the setup for leaf 30 on the B carriage is shown in Figure 3.5(b).

3.6.3 15.0 cm Leaf Extension

For this reproducibility test, the edge of the extended leaf was extended 15 cm from the rest of the leaves in the carriage. 15 cm is the maximum distance that any single leaf can be extended from the rest of the leaves in the carriage. The extended leaf was set to the position that gave an approximately fifty percent response on the diode array. The carriage not containing the leaf was set to a distance of 7.5 cm from the edge of the extended leaf. Twenty-five readings were taken, again retracting and re-extending the multileaf collimator between measurements. An example of the multileaf field for leaf 30 of carriage B is shown in Figure 3.5(c).

3.7 Testing Multileaf Positional Reproducibility Off Axis

To test positional reproducibility off axis, each leaf being tested was extended 10 cm across the central axis. The secondary collimators were set to a 15 cm by 15 cm field size around the extended leaf. The diode array was at a 100 cm source to surface distance. The same six leaves were tested, three on each carriage. To determine the approximate fifty percent position for each leaf, the diode array was placed so that the leaf would travel directly over a single row of



(a) 2 cm leaf extension

(b) 7.5 cm leaf extension

(c) 15 cm leaf extension

Figure 3.5. Multileaf collimator leaf extensions: (a) Leaf 30 is extended 2 cm from the rest of carriage B, (b) Leaf 30 is extended 7.5 cm from carriage B, and (c) Leaf 30 is extended 15 cm from carriage B. Carriage A stays in the same position for all three leaf extensions.

diodes. The same diode used in the central axis test was placed directly under the leaf edge. The diode array was exposed to 30 monitor units of 10 MV photons with and without the leaf extended. The diode array was moved laterally until the diode gave an approximately fifty percent response with the leaf extended relative to the response in the open field. Once the approximate fifty percent position was determined, 25 readings were recorded. The multileaf collimator was retracted and re-extended between each of the 25 readings.

The 2 cm, 7.5 cm, and 15 cm leaf extensions were tested with each leaf extended to 10 cm off axis. Twenty-five readings were taken for each leaf in each of the three leaf extension positions. The carriage not containing the leaf to be extended was set to a distance of 7.5 cm from the edge of the extended leaf and not moved for the different leaf extensions.

CHAPTER 4

RESULTS

4.1 Diode Array Output Variability

To determine the variability in the output of the diodes in the diode array, ten measurements were taken and compared. Figure 4.1 shows the fluctuation in the response of the diodes along the central axis column in the diode array. Figure 4.2 shows the fluctuation in the response of the diodes along the central axis row in the diode array. Each reading was normalized to the average of the ten readings for each of the diodes. Only the center diode in the array was used for this project, but the diodes along the central axis row and column were also compared to show that the center diode had the same variability as the other diodes in the array.

4.2 Edge Function Comparisons

Before analyzing the multileaf positional reproducibility, a standard to convert the change in diode response to a corresponding distance was developed. Several different factors were considered in this process. An edge function developed with film was needed to determine the distance corresponding to the change in diode response because film response has a much finer resolution than diode response. However, in order to use film to estimate the distance, the edge function from the diode array had to be shown to be comparable to the edge function from film. Once the edge functions were found to be comparable, the next step was to determine the edge function or functions that should be used to evaluate the distance corresponding to the diode response. To do this, edge

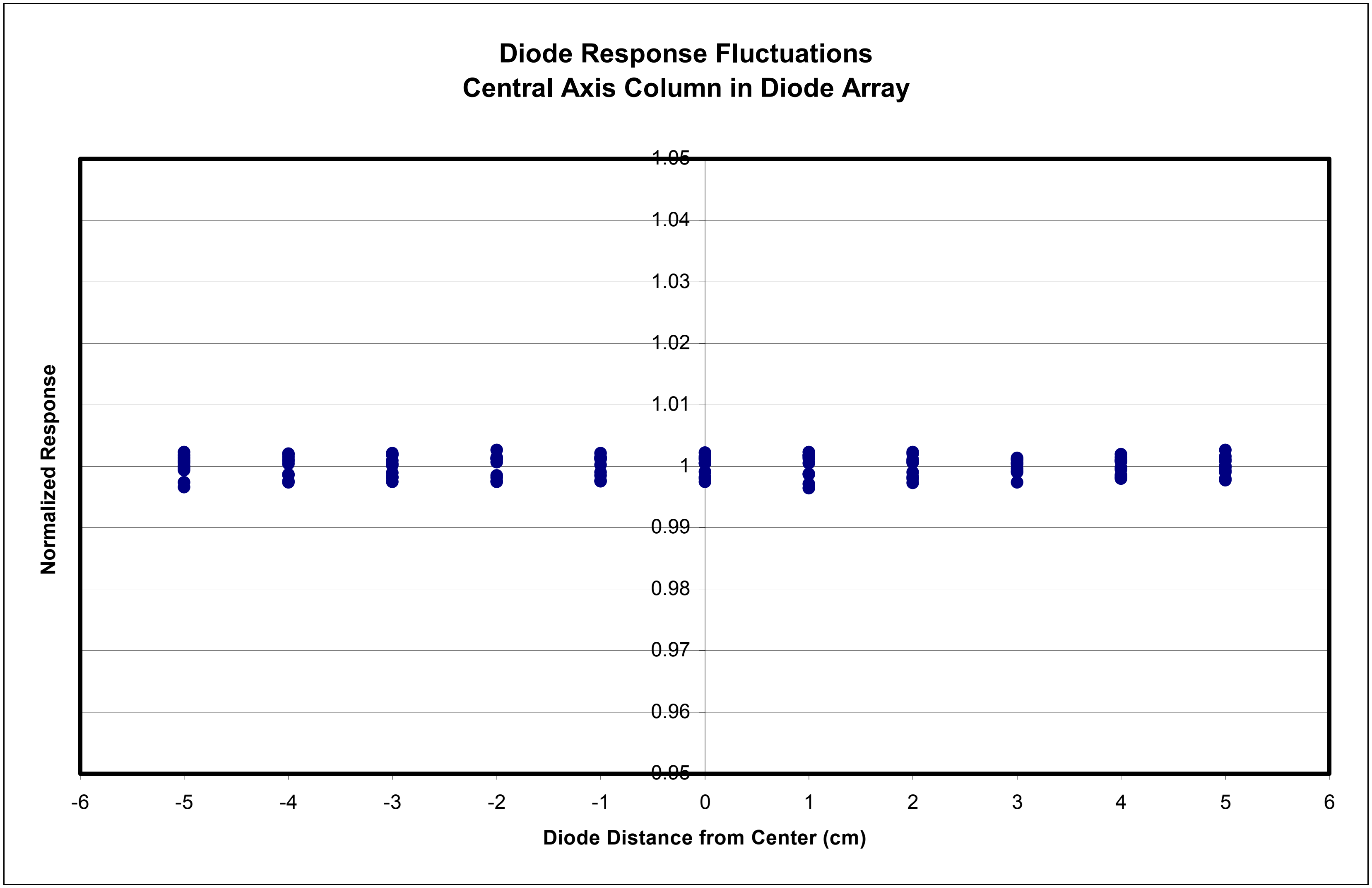


Figure 4.1. Fluctuations in the diode response along the central axis column of the diode array. Each point corresponds to a different acquisition for a particular diode normalized to the average of ten readings for that diode.

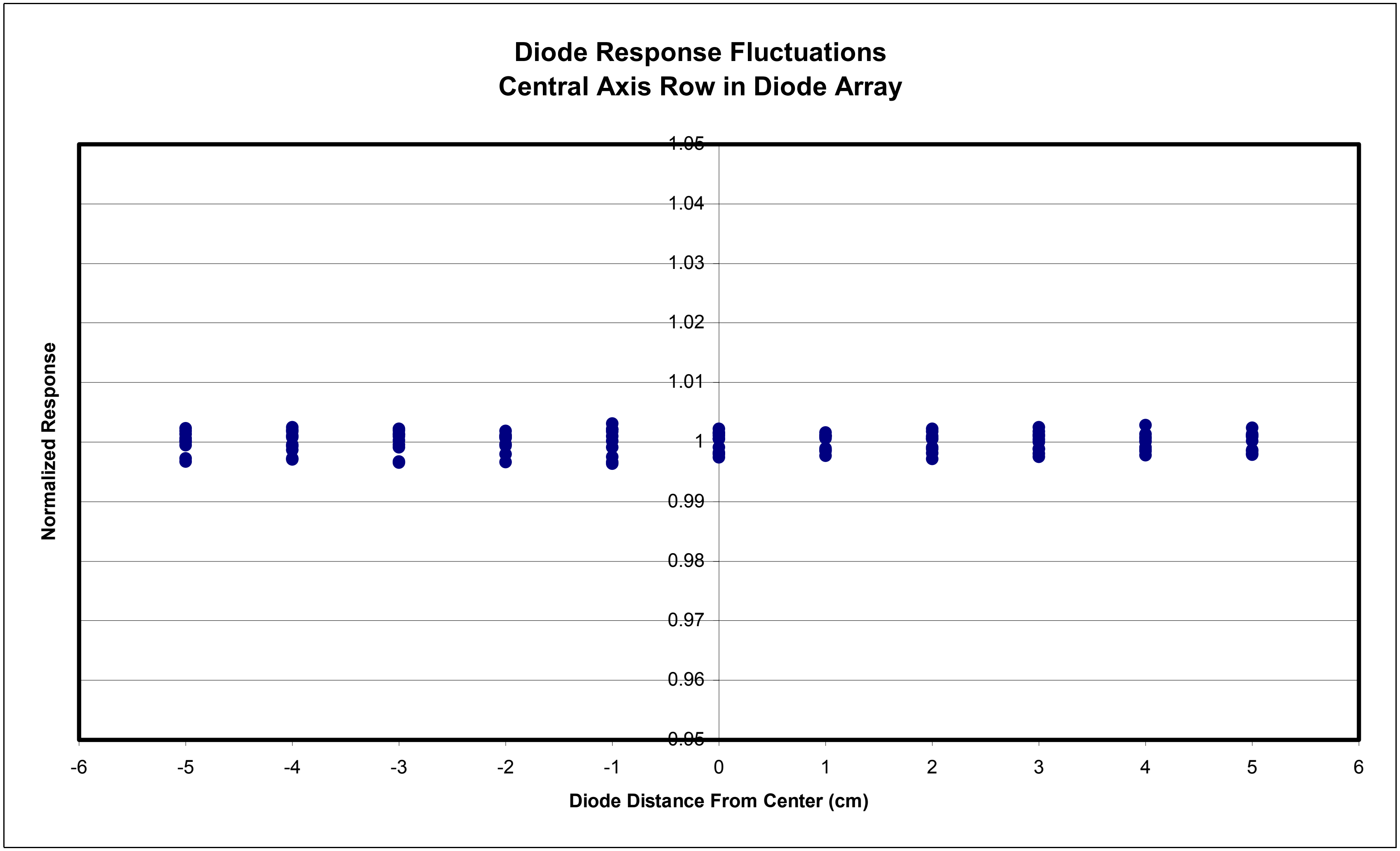


Figure 4.2. Fluctuations in the diode response along the central axis row of the diode array. Each point represents a different acquisition for a particular diode normalized to the average of ten readings for that diode.

functions were compared for both central axis and off axis positions for each leaf. The edge functions were also compared between the different leaves to determine whether or not they could be represented by a single standard function. Once the edge functions to be used were determined, the response from the diode array could then be converted to a distance for every situation tested for each leaf.

4.2.1 Film Edge Function vs. Diode Array Edge Function

To determine whether the edge functions from film data could be used to determine leaf positional reproducibility from the diode array measurements, edge functions from film and from the diode array were compared. The data from both film and the diode array were normalized to zero at a distance of 2.4 cm under the leaf and normalized to one at 2.4 cm inside the open field. As seen in Figure 4.3, the shapes of both curves appear to be very similar, especially in the region below the fifty percent line. The diode array data were acquired twice because of some irregularity in the region of 100% dose. The diode response was irregular in this region for both data acquisitions. This could possibly be related to the method in which the edge function data were acquired with the diode array, i.e. it could be attributable to the leaf motion. Figure 4.3 also illustrates that the film data have a much finer resolution than the diode array data. The film was scanned with a resolution of 169 microns. The resolution of the diode array was around two millimeters, which was the distance the leaf was moved between each diode reading when determining the edge function. Both functions shown were from leaf 30 on the B carriage. Because the two edge functions had the same basic slope in the linear region around the fifty percent line, it was inferred that the edge

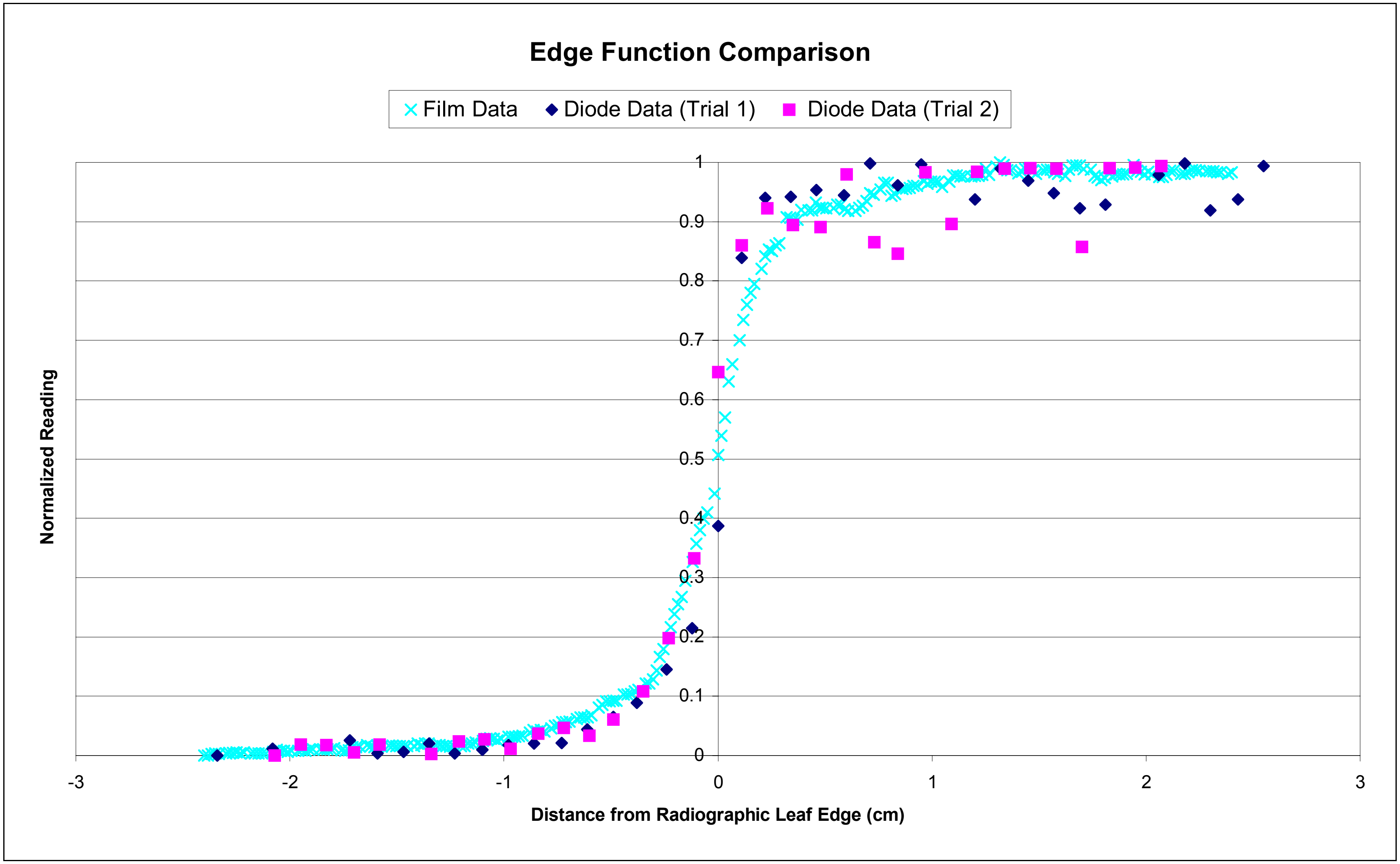


Figure 4.3. Comparison of edge functions produced by film and by the diode array. Data are normalized to zero under the leaf and to one 2.4 cm inside the open field. The diode array edge function was measured twice.

functions fitted to the film were a good estimate of the edge function and therefore the response determined by the diode array.

4.2.2 Central Axis Functions vs. Off Axis Functions

Edge functions were fitted using equations 3.1 and 3.2 for each leaf to the measured central axis data and to the data measured 10 cm off axis. The data used to fit the functions were normalized to zero at a position 2.4 cm under the leaf and normalized to one at a position 2.4 cm inside the open area of the field. To compare the fitted functions between leaves, two separate fitted functions were chosen as the standard functions, one for the leaf edge at the central axis and one for the leaf edge 10 cm off axis; in this case leaf 30A was used. The fitting parameters for the standard functions are shown in Table 4.1. The seventy percent and thirty percent positions were then determined from the functions fitted to the measured data for each individual leaf. In order to determine the seventy percent and thirty percent positions, the inner and outer fitted functions were inverted and are shown in equations 4.1 and 4.2.

Eq. 4.1 Inner: $d = \ln [2 * (1-P)] / -a_{in}$

Eq. 4.2 Outer: $d = \ln [2 * P] / -a_{out}$

Where d is the distance from the radiographic edge and P is the film response normalized to the maximum value in an open field.

Table 4.1. Standard function fitting parameters.

	Central Axis Function	Off Axis Function
a_{in}	-4.785	-7.226
a_{out}	-4.564	-3.498

The seventy percent and thirty percent positions shown in Table 4.2 and Table 4.3 were then plotted in Figure 4.4 along with the chosen central axis and off axis standard functions to compare the fits between the leaves. As seen in Figure 4.4, the central axis function has a different slope than the 10 cm off axis function. This suggested that two different curves should be used to determine the distance error in leaf positional reproducibility. One standard function should be used to determine the distance for all of the tests in which the leaves were extended to the central axis and a separate function should be used for the leaves in the 10 cm off axis position. The steep slope of both curves also implied that the diode array must be positioned within 2 mm of the fifty percent location to ensure that the diode being used for measurement is not in the shoulder region of the curve where the distance estimate would be more uncertain.

Table 4.2. Distances corresponding to seventy percent intensity. Values are calculated from equations 4.1 and 4.2.

Leaf Number	Central Axis	10 cm Off Axis
30A	-1.07 mm	-0.71 mm
30B	-1.17 mm	-0.73 mm
19A	-0.91 mm	-0.65 mm
19B	-0.80 mm	-0.78 mm
6A	-0.91 mm	-0.76 mm
6B	-0.83 mm	-0.85 mm

Table 4.3. Distances corresponding to thirty percent intensity. Values are calculated from equations 4.1 and 4.2.

Leaf Number	Central Axis	10 cm Off Axis
30A	1.12 mm	1.46 mm
30B	1.43 mm	1.45 mm
19A	1.07 mm	1.06 mm
19B	1.00 mm	1.30 mm
6A	0.999 mm	1.08 mm
6B	1.03 mm	1.23 mm

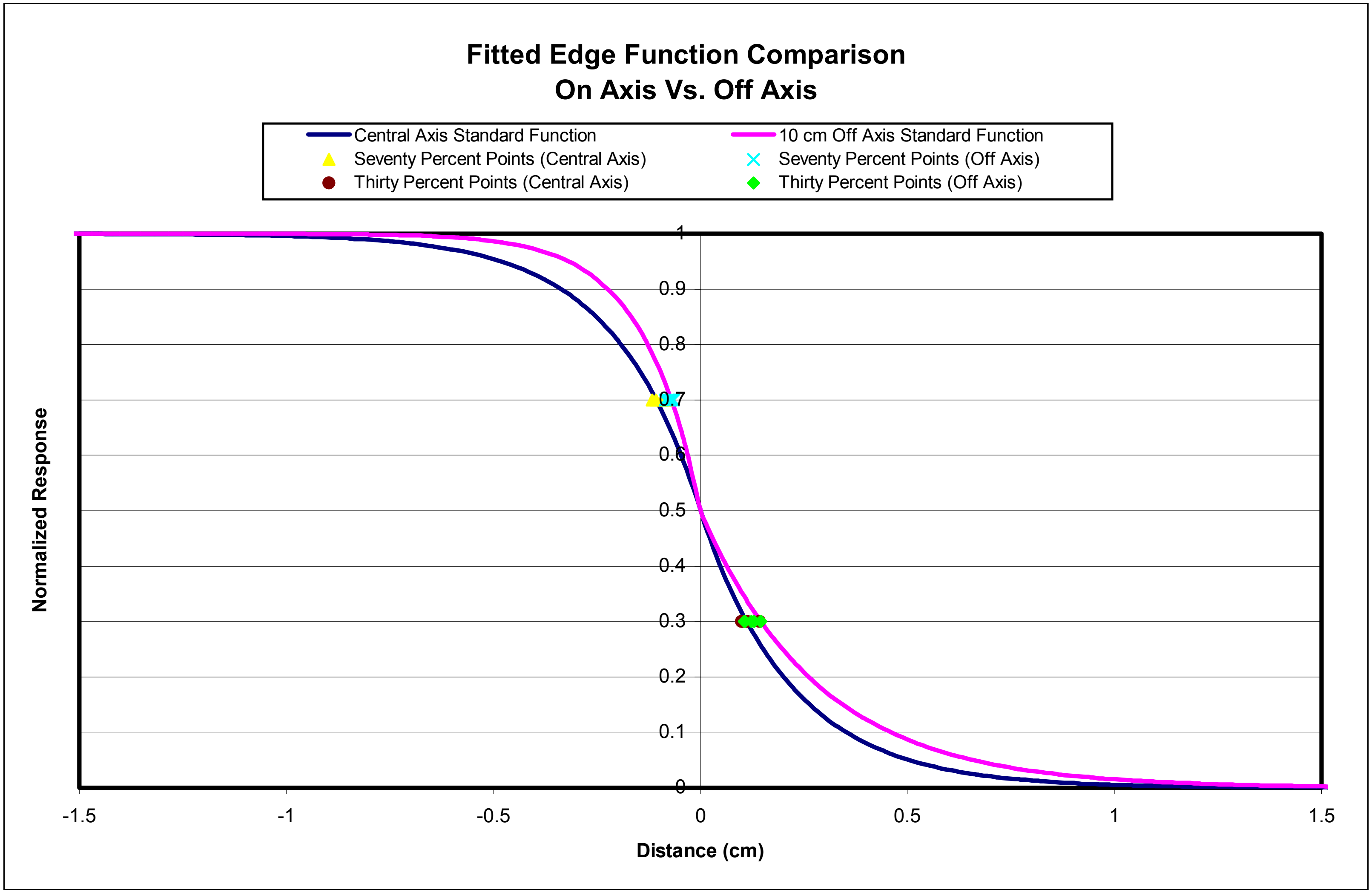


Figure 4.4. Comparison of edge functions fitted to central axis and 10 cm off axis data. Seventy percent and thirty percent points are from fitted functions for each of six leaves tested. Data are normalized to zero under the leaf and to one 2.4 cm inside the open area of the field.

4.3 Reproducibility on the Central Axis

Reproducibility of leaf position with the leaf extended to the central axis was tested for three different leaves on each of the two carriages. Reproducibility was also tested for three different leaf extensions from the carriage for each of the six different leaves. The diode responses were converted to a corresponding distance using equations 4.1 and 4.2 and the values for a_{in} and a_{out} shown in Table 4.1 for the central axis standard function. The standard deviation of the diode readings were calculated as the deviation from the mean of twenty-five readings taken with a single leaf extended to the central axis. All data were normalized to an open field reading before the standard deviations were calculated. The standard deviations of the corresponding distances were calculated through propagation of error. Propagation of error is a technique used to determine the error in a final result by deriving the error in each measurement or number used to get that result. The error in the distance calculation is the partial derivative of equations 4.1 or 4.2 multiplied by the standard deviation of the diode readings. Table 4.4 lists the standard deviations in the diode response as well as the standard deviations of the distances calculated from the fitted functions.

4.4 Reproducibility 10 cm Off Axis

Each of the six leaves was extended to 10 cm across the central axis to determine the reproducibility of leaf position off axis. Twenty-five readings were taken for each leaf with three different leaf extensions from the carriage. In each case the edge of the extended leaf was at a position 10 cm across the central axis. The standard deviations of the diode readings are calculated as described for the central axis case in section 4.3. The standard deviations for the corresponding distances were once again calculated through propagation of error using equations 4.1 and 4.2. The standard deviations for the diode response as well as for the calculated distance are shown in Table 4.5.

Table 4.4. Standard deviations of the diode responses and corresponding distances on the central axis. The diode response standard deviation is the deviation from the mean of twenty-five readings after data were normalized to an open field reading. The standard deviation of the distance is calculated by propagation of error.

Leaf Number	Leaf Extension From Carriage	Diode Response Standard Deviation	Calculated Distance Standard Deviation (mm)
30A	2.0 cm	0.013	0.060
	7.5 cm	0.011	0.051
	15 cm	0.012	0.055
30B	2.0 cm	0.010	0.045
	7.5 cm	0.018	0.081
	15 cm	0.016	0.071
19A	2.0 cm	0.011	0.051
	7.5 cm	0.010	0.043
	15 cm	0.011	0.052
19B	2.0 cm	0.012	0.060
	7.5 cm	0.011	0.052
	15 cm	0.009	0.045
6A	2.0 cm	0.017	0.081
	7.5 cm	0.011	0.052
	15 cm	0.010	0.046
6B	2.0 cm	0.014	0.060
	7.5 cm	0.012	0.052
	15 cm	0.009	0.040

Table 4.5. Standard deviation of the diode responses and corresponding distances at 10 cm off axis. The diode response standard deviation is the deviation from the mean of twenty-five readings after data were normalized to an open field reading. The standard deviation of the distance is calculated by propagation of error.

Leaf Number	Leaf Extension From Carriage	Diode Response Standard Deviation	Calculated Distance Standard Deviation (mm)
30A	2.0 cm	0.020	0.060
	7.5 cm	0.013	0.078
	15 cm	0.014	0.043
30B	2.0 cm	0.014	0.080
	7.5 cm	0.011	0.033
	15 cm	0.010	0.062
19A	2.0 cm	0.011	0.069
	7.5 cm	0.009	0.053
	15 cm	0.009	0.057
19B	2.0 cm	0.008	0.047
	7.5 cm	0.011	0.063
	15 cm	0.011	0.064
6A	2.0 cm	0.010	0.027
	7.5 cm	0.013	0.036
	15 cm	0.011	0.030
6B	2.0 cm	0.008	0.022
	7.5 cm	0.011	0.032
	15 cm	0.010	0.030

CHAPTER 5

DISCUSSION

Determination of the fluctuations in the response of each diode under the same conditions is important because a large variation in the diode response would make it impossible to determine whether the reading is varying because of an error in leaf position or just a variance of the diode response. The variability of the diode response was found to be less than seven tenths of a percent for any given diode. The distance calculated from the standard function that corresponds to 0.7% is, on average, 0.03 mm. This distance is much smaller than the 0.2 mm recommended tolerance. The diode array should therefore be able to detect small changes in leaf position without concern for the variability in the diode response.

When comparing the edge function produced by the diode array to the edge function produced by film, there appears to be a slight discrepancy in the shoulder region above sixty percent. This difference in the functions might result from the manner in which the data were collected. The film edge function was measured by a single exposure of 30 cGy to the film with a single leaf extended. The diode array edge function was determined by moving the leaf across a single diode in 1 mm increments through a total distance of 4.8 cm. The edge function produced by the diode array does not have as fine a resolution as the film does. Also, there is some fluctuation in diode response as the curve is approaching 1.0 in the open field. For the purposes of this research, the edge function produced using radiographic film is believed to be a more accurate representation of the actual edge function of the leaf and can also be used in conjunction with the diode array to determine distances.

The tests for reproducibility were designed to test the dependence of leaf positional reproducibility under several different conditions. Leaves in different positions within a single carriage were tested to determine whether the location of the leaf would make leaf position less reproducible. The same leaves in the opposite carriage were tested to determine whether the two carriages had a different reproducibility between them. Also the three leaves on each carriage were tested with three separate extensions from the other leaves in the carriage to determine whether the distance traveled by the leaf beyond the carriage would have an effect on the reproducibility. All of these tests were conducted with the leaf extended to the central axis and with the leaf extended 10 cm beyond the central axis to compare the reproducibility between these two leaf positions. The results show that the standard deviations of the diode readings for all of the tests conducted are less than two percent. There is no apparent dependence of leaf reproducibility on the leaf extension, location in the carriage or central axis versus off axis position. The standard deviation of the distances calculated from the standard curve is less than 0.1 mm, which is well within the recommended tolerance of 0.2 mm.

The small variability in the results of each of the different tests indicates that the leaf position is very reproducible. When the readings from the diode array are converted into distances using the pre-determined standard functions, it is shown that the diode array is capable of detecting very small shifts in leaf position, smaller than tenths of a millimeter. The diode array is therefore sensitive enough to shifts in leaf position to be effective in a quality assurance process.

CHAPTER 6

CONCLUSIONS

It has been shown in this research that the edge function of a single leaf in the multileaf collimator can be measured using film. A standard function can be used to represent all of the leaves on the central axis and a different standard function should be used to represent the leaves at a position 10 cm off axis. It has also been shown that the edge function produced by the film is applicable to the data acquired from the diode array. Using this approach, the data from the digitized film edge function can be fitted to a function and then used to determine a distance corresponding to the readings from the diode array.

The method described above is sensitive enough to detect errors in leaf position as small as a tenth of a millimeter. The tolerance of variability in leaf position is recommended in the literature to be 0.2 mm to ensure proper dose delivery. The diode array is therefore sensitive enough to determine the positional reproducibility of individual leaves at locations both on and off the central axis.

This method can be developed into a quality assurance procedure that could quickly and easily detect errors in leaf positional reproducibility before it exceeds the tolerance of the machine. Before a quality assurance procedure is adopted to test the multileaf collimator, it must meet certain requirements. First, it must be sensitive enough to detect small changes, which the diode array has already been shown to do. Second, it must be quick and easy enough to be performed on a regular basis in a clinical setting. The diode array is faster than film for quality assurance purposes because the data can be analyzed directly without the inconvenience of having to develop and digitize film. The diode array can also be easily mounted to the gantry or aligned on the treatment couch. The person performing the quality assurance procedure would not have to re-enter the room between sequential exposures. The multileaf collimator can be programmed to move to certain test positions and the diode array readings can be taken and recorded from outside the treatment room. Use of a diode array can therefore reduce the acquisition time as well as the time required for analysis.

A routine quality assurance procedure to test multileaf positional reproducibility can be very useful in a clinical setting. Machine tolerances are set to 2 mm error in leaf position. As stated previously, a 2 mm error can translate into large dose errors across the entire treatment field. The quality assurance procedure described here could catch very small leaf errors that could be corrected before any dose delivery errors are made. Also, leaf errors caused by an individual leaf's motor failure can be caught before the motor fails completely. In cases where the motor becomes inoperable, the machine must be down until the motor is replaced. If the error is caught before the motor fails, the motor can be replaced in the machine's off time to avoid any patient treatment delays.

In conclusion, the diode array can be used in conjunction with an edge function determined from radiographic film to develop a quality assurance procedure. This procedure using the diode array is sensitive enough to measure small shifts in leaf position and can be performed in an acceptable amount of time to easily take routine measurements.

REFERENCES

Boyer, Arthur, Peter Biggs, James Galvin, Eric Klein, Thomas LoSasso, Daniel Low, Katherine Mah, and Cedric Yu. 2001. *Basic Applications of Multileaf Collimators: Report of the AAPM Radiation Therapy Committee Task Group No. 50.* Madison: Medical Physics Publishing.

Budgell, G. J., J. H. L. Mott, P. C. Williams, and K. J. Brown. "Requirements for leaf position accuracy for dynamic multileaf collimation." *Physics in Medicine and Biology* 45 (2000): 1211-1227.

Chui, Chen-Shou, Spiridon Spirou, and Thomas LoSasso. "Testing of dynamic multileaf collimation." *Medical Physics* 23, no. 5 (May 1996): 635-641.

Essers, Marion and Ben Munheer. "*In Vivo* Dosimetry During External Photon Beam Radiotherapy." *International Journal of Radiation Oncology Biology Physics* 43, no. 2 (1999): 245-249.

Hansen, Vibeke, Philip Evans, Geoffrey Budgell, Judith Mott, Peter Williams, Marco Brugmans, Frits Wittkamper, Ben Mijnheer, and Kevin Brown. "Quality assurance of the dose delivered by small radiation segments." *Physics in Medicine and Biology* 43 (1998): 2665-2675.

Hendee, William, and Geoffrey Ibbott. *Radiation Therapy Physics,* 2d ed. St. Louis: Mosby-Year Book, Inc., 1996.

Jordan, Thomas, and Peter Williams. "The design and performance characteristics of a multileaf collimator." *Physics in Medicine and Biology* 39 (1994): 231-251.

Jursinic, Paul A. "Implementation of an *in vivo* diode dosimetry program and changes in diode characteristics over a 4-year clinical history." *Medical Physics* 28, no. 8 (August 2001): 1718-1726.

Khan, Faiz M. *The Physics of Radiation Therapy*, 2nd ed. Baltimore: Lippincott, Williams & Wilkins, 1994.

Klein, Eric E., William B. Harms, Daniel A. Low, Virgil Willcut, and James A. Purdy. "Clinical Implementation of a Commercial Multileaf Collimator: Dosimetry, Networking, Simulation, and Quality Assurance." *International Journal of Radiation Oncology Biology Physics* 33, no. 5 (1995): 1195-1208.

LoSasso, Thomas, Chen-Shou Chui, and C. Clifton Ling. "Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing intensity modulated radiotherapy." *Medical Physics* 25, no. 10 (Oct. 1998): 1919-1927.

LoSasso, Thomas, Chen-Shou Chui, and C. Clifton Ling. “Comprehensive quality assurance for the delivery of intensity modulated radiotherapy with a multileaf collimator used in the dynamic mode.” *Medical Physics* 28, no. 11 (Nov. 2001): 2209-2219.

Low, Daniel, Jason Sohn, Eric Klein, Jerry Markman, Sasa Mutic, and James Dempsey. “Characterization of a commercial multileaf collimator used for intensity modulated radiation therapy.” *Medical Physics* 28, no. 5 (May 2001): 752-756.

Papatheodorou, Spiridon, Jean-Claude Rosenwald, Sofia Zefkili, Marie-Claude Murillo, Jean Drouard, and Genevieve Gaboriaud. “Dose calculation and verification of intensity modulation generated by dynamic multileaf collimators.” *Medical Physics* 27, no. 5 (May 2000): 960-971.

Perez, Carlos A., M.D. and Luther W. Brady, M.D. *Principles and Practice of Radiation Oncology*, 2nd ed. Philadelphia: J. B. Lippincott Company, 1992.

Sun, Jiansheng and Yunping Zhu. “Study of Dosimetric Penumbra Due to Multileaf Collimation on a Medical Linear Accelerator.” *International Journal Radiation Oncology Biology Physics* 32, no. 5 (1995): 1409-1417.

Zhu, T. C., L. Ding, C. R. Liu, and J. R. Palta. “Performance evaluation of a diode array for enhanced dynamic wedge dosimetry.” *Medical Physics* 24, no. 7 (July 1997): 1173-1180.

VITA

Kara Ferachi was born in Lake Charles, Louisiana, in 1976 and resided in Dry Creek, Louisiana, until 1994. After graduating from East Beauregard High School in May of 1994, she attended Louisiana Tech University in Ruston, Louisiana. Kara graduated Magna Cum Laude from Louisiana Tech University in May of 1998 with a Bachelor of Science in Biology.

After taking several graduate courses at McNeese State University in Lake Charles, Louisiana, Kara entered the medical physics graduate program at Louisiana State University in the fall semester of 1999. Kara is currently completing the requirements for a Master of Science in the department of Physics and Astronomy at Louisiana State University. She plans to graduate in May of 2003.