INTRAOPERATIVE RADIATION THERAPY: CHARACTERIZATION & APPLICATION

THESIS

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

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Master of Science in Nuclear Engineering

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Acknowledgements

This report presents a summary of the work I completed for the USAF Medical Clinic at Wright-Patterson AFB. My task was define and perform the dosimetry measurement required to characterize Intraoperative Radiation Therapy (IORT) applicators.

Many people helped make this project a success. Lieutenant Colonel John Swanson and First Lieutenant Ken Wohlt of the USAF Medical Center gave me the opportunity to characterize the Intraoperative Radiation Therapy (IORT) system. During the course of the project they provided me with a thorough introduction to the field of medical physics. Dr. George John of the Air Force Institute of Technology provided steadfast guidance and moral support throughout the course of the project. Mr. Robert Dahl, Dr. Dave Mellenberg and Dr. Ed McCullough of the Mayo Clinic generously shared their experiences with IORT. Their pioneering efforts served as the basis for all my work. Mr. John Brohas of the AFIT Model Fabrication Shop aided my efforts considerably by building various pieces of equipment used in this project. Finally, I would like to thank my wife, Roberta, for enduring the trials and tribulations of my AFIT education.

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Notation

cGy - centiGray

dmax - Location of Maximum Dose Along Central Axis

EBRT - External Beam Radiation Therapy

IORT - Intraoperative Radiation Therapy

MGH - Massachusetts General Hospital

MU - Monitor Unit

OD - Optical Density

SD - Standard Density

SSD - Source to Surface Distance

Abstract

The goal of this project was to define and perform the dosimetry measurements required to characterize a set of 18 applicators for use in Intraoperative Radiation Therapy (IORT). IORT is one of the newest tools in the fight against cancer. In IORT, malignant tumors are exposed directly to high-energy electrons delivered through a specially designed applicator mounted on a linear accelerator.

The medical physicist must provide an adequate description of the dose delivery characteristics for every combination of IORT applicator and electron-beam energy. Briefly, the characteristics of interest include: isodose charts, output factors, effective Source-to-Surface-Distances (SSDs), offset factors, and Central-Axis (CAX) profiles.

Each characteristic is important in the IORT treatment planning process. Isodose charts are used to help select the right combination of IORT applicator and electron-beam energy. Output factors and the offset factors are used to scale the prescribed dose to the appropriate number of monitor units (MUs). CAX profiles are used to find surface dose factors, output factors, and x-ray dose factors.

Radiographic film is used to obtain the iosdose charts and CAX profiles. Effective SSDs are measured using a parallel-plate ionization chamber. In general the results are comparable to those found by personnel at Mayo Clinic for their IORT system. The only difference is the observation that effective SSDs are dependent upon the diameter of the IORT applicator and the electron-beam energy.

INTRAOPERATIVE RADIATION THERAPY: CHARACTERIZATION & APPLICATION

I. INTRODUCTION

Goal of the Project

The primary goal of this project was to define and perform the dosimetry measurements required to characterize a set of 18 IORT applicators. The secondary goal was to provide a basic introduction to Intraoperative Radiation Therapy (IORT). Every effort was made to follow conventional practice with regards to terminology and equipment.

The terminology and methods described in this report are consistent with the work done by medical physicists at Mayo Clinic and Massachusetts General Hospital (MGH). Mayo Clinic and MGH personnel pioneered the development and application of IORT in the United States. This effort draws heavily on the collective expertise of the medical physicists at the Mayo Clinic.

The primary pieces of equipment for characterizing IORT applicators include: radiographic film, a phantom, an automatic film processor, a scanning densitometer, an ionization chamber, and an electrometer. It is assumed the reader is familiar with the basic theory and operational characteristics of each piece of equipment.

Approach

The medical physicist must provide the radiation oncologist and surgeon with isodose charts, output factors, effective SSDs, offset factors, and central axis profiles for every combination of IORT applicator and electron-beam energy. Although several approaches are possible, the use of radiographic film is undoubtedly one of the most familiar and convenient. In this effort, radiographic film is used to determine isodose charts, output factors, and central axis profiles. The effective SSDs are determined more precisely using an ionization chamber and electrometer.

Radiographic film is well suited for the relative dosimetric measurements which are required. Kahn writes,

> "Film dosimetry offers a convenient and rapid method of obtaining a complete set of isodose curves in the plane of the film. Its use for determining electron beam dose distributions is well established. It has been shown that the depth dose distributions measured by using film agree well with those by ion chambers when the latter measurements are corrected (for changes in the stopping power ratio). The energy independence of film may be explained by the fact that the ratio of collision stopping power in emulsion and in water varies slowly with electron energy. Thus, the optical density of the film can be taken as proportional to the dose with essentially no corrections." (4:309).

The use of film requires determination of the film's characteristic curve and diligent monitoring of the film processor.

The characteristic curve relates the optical density (OD) of the developed film to the given dose. Strictly speaking, the characteristic curve is a plot of the standard density (SD) versus given dose. Appendix A develops an expression for SD in terms of OD. The characteristic curve may be linear or nonlinear with dose depending upon the film emulsion. Horton suggests the use of either Kodak XTL or Translite film (3:41-42). Based on measurements made during this study, Kodak XTL-2 film is a good choice. Its characteristic curve shows a linear response for doses of up to 10 Monitor Units (MUs) and no energy dependence for electron-beam energies of 9-, 12-, 16-, and 20-MeV. Figure 1 shows the experimentally-measured characteristic curves for Kodak XTL-2 film.

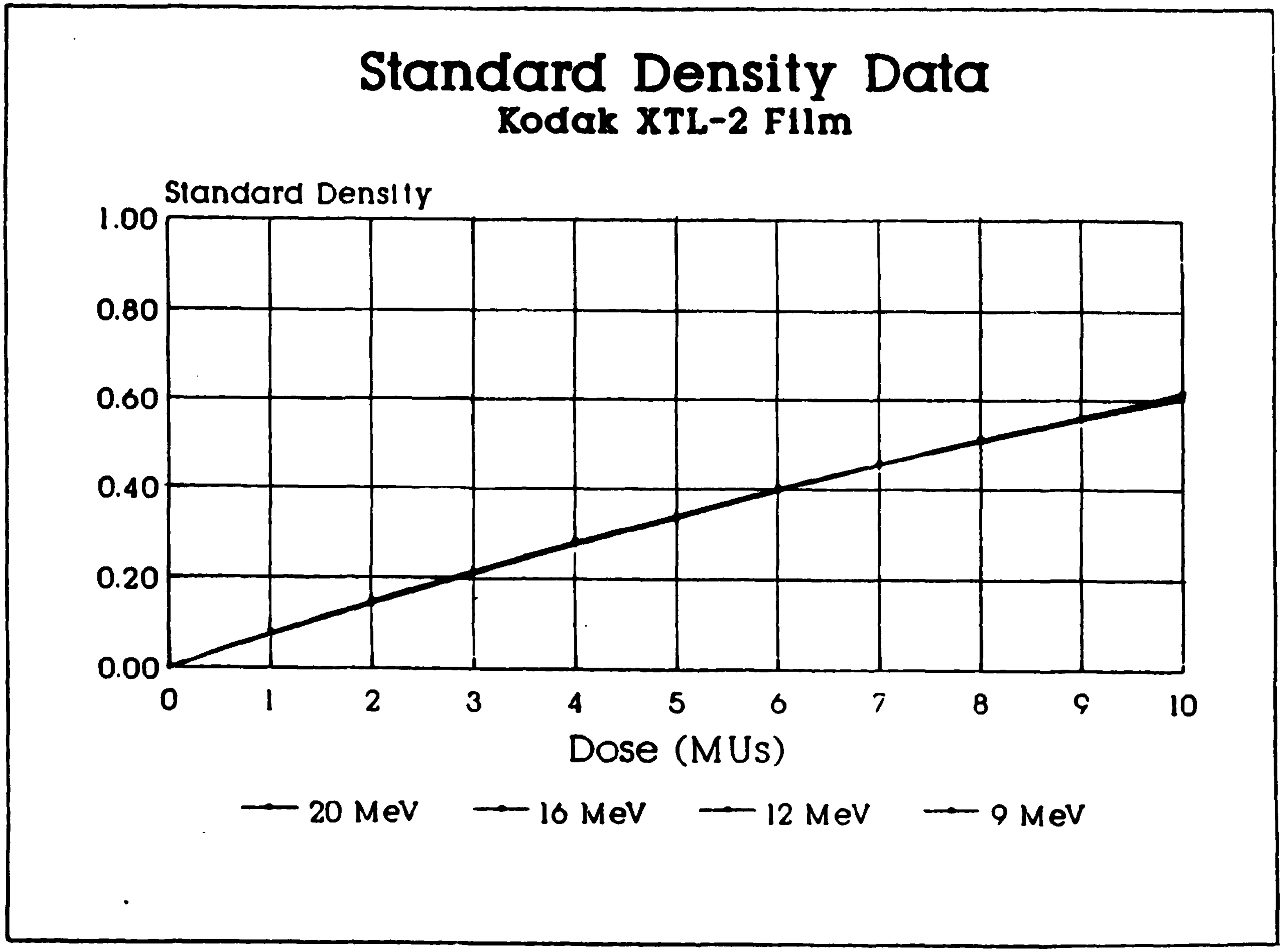

Figure 1 - Characteristic Curves - Kodak XTL-2 Film

Monitoring of the film processor is accomplished through the use of control films. Control films consist of a set of identically exposed and handled sheets of film. By periodically developing one of the control films and measuring its OD with a densitometer, it is possible to detect any significant changes in processing conditions. In this study, 16 control films were used to monitor the stability of the automatic film processor. All the film work was completed within a 12 hour period. Over 90 sheets of film were developed. Despite the heavy load on the processor, the ODs of the control films showed a variation of only +/- 2.0%. Although this is slightly greater than the +/- 1.5% variation for a set of five films which were developed consecutively, the performance of the film processor is acceptable. Both figures are better than the +/- 3.0% variation reported by Horton for film (3:41-42). The use of film is justified since it is possible to predict its response through the characteristic curve and to monitor the film processor through the use of control films.

Plan of the Report

This report is geared to the needs of the medical physicist faced with the challenge of characterizing and using IORT applicators for the first time. Since IORT is a new technique, the reader is probably not familiar with the specific equipment used in IORT. Chapter II covers the basics of IORT in terms of technique and equipment. Chapter III explains the "What?", "Why?" and "How?" for each important dose delivery characteristic. Chapter IV applies the concepts discussed in Chapter III by showing how to translate a prescribed dose into the appropriate number of Monitor Units (MUs). Chapter V draws conclusions and makes recommendations based upon the work completed.

II. Clinical Aspects of IORT

Overview of Method

Intraoperative Radiation Therapy (IORT) is one of the newest tools in the fight against cancer. In IORT, malignant tumors are exposed directly to high-energy electrons delivered through a specially designed applicator mounted on a linear accelerator. A surgical incision allows insertion of the IORT applicator into the patient. Radiosensitive normal tissue is either moved out of the way or shielded with thin lead sheets. The surgeon and radiation oncologist choose an appropriately sized applicator and electron-beam energy such that the entire tumor receives the prescribed dose. After positioning the applicator in the patient, the patient support assembly (PSA) and the linear accelerator gantry are maneuvered until the applicator is docked within the docking tube attached to the linear accelerator. A dose of 1000 to 2000 cGy is then delivered to the tumor in two or three consecutive segments.

Advantages of IORT

When combined with External Beam Radiation Therapy (EBRT) and surgical resection, IORT gives the radiation oncologist a better way of dealing with certain types of cancer for which local control is difficult to obtain. Notably, carcinomas of the pancreas, stomach, colon, and rectum, and sarcomas of soft tissue are prime candidates for IORT (2:131). IORT goes a step beyond EBRT by providing a means to apply a large dose of radiation directly to a tumor or tumor bed while sparing normal tissue.

By surgically exposing the tumor, the radiation oncologist has the opportunity to assess the extent of the disease more accurately. Irradiation of the tumor bed following surgical resection helps prevent recurrence of the disease by suppressing the residual tumor. Most often, IORT will be used in conjunction with EBRT and surgical resection.

IORT Equipment

The principal pieces of equipment needed for IORT include a linear accelerator and an IORT delivery system. The linear accelerator supplies a high-energy electron beam, while the IORT delivery system provides a means of directing the electron beam onto the tumor.

Linear Accelerator The linear accelerator at the USAF Medical Center is a Varian Clinac-1800. Figure 2 identifies the major components of the Clinac-1800 and defines a set of reference axes.

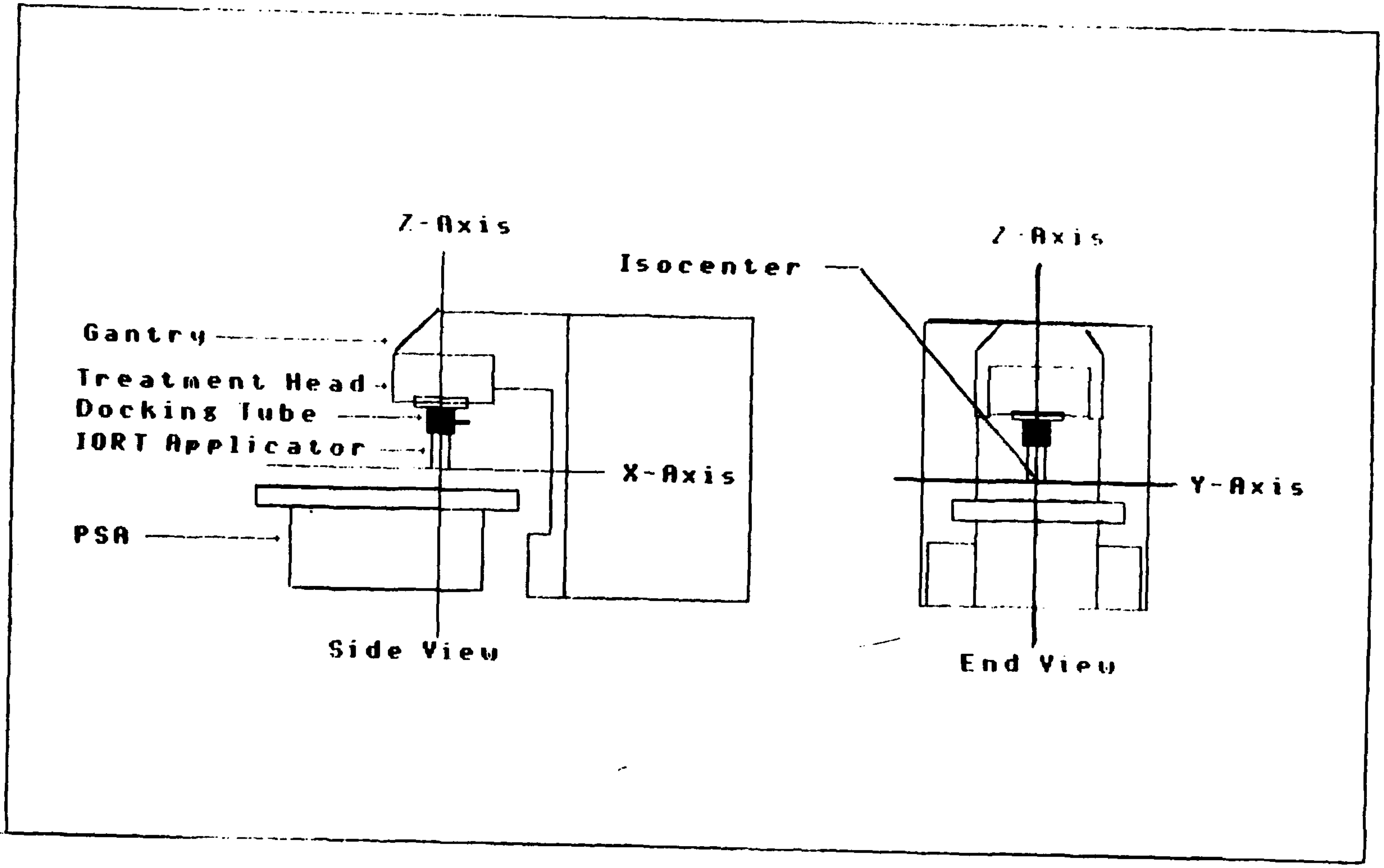

Figure 2 - Linear Accelerator and Reference Axes

Two issues concerning the proper use of the linear accelerator are choosing the appropriate electron-beam energy and setting the variable collimator jaws in the treatment head. Each is addressed separately.

The choice of electron-beam energy is dictated by the depth of the tumor. The Clinac-1800 is capable of producing electron-beam energies of 6-, 9-, 12-, 16-, and 20-MeV. It is not likely the 6-MeV electron-beam will be used in IORT due to its very limited depth of penetration in tissue. Experience at Mayo Clinic confirms the limited application of the 6-MeV electron-beam. In a review of 214 cases, only two treatments involved the 6-MeV electron-beam (6). As a result, only electron-beam energies of 9-, 12-, 16-, and 20-MeV are considered in this study.

The dose delivery characteristics of each IORT applicator are influenced by the size of the aperture presented by the adjustable set of collimator jaws in the treatment head of the linear accelerator. Figure 3 depicts the pathway of the electron beam through the linear accelerator and IORT applicator. It shows the location of the fixed and adjustable collimators within the treatment head.

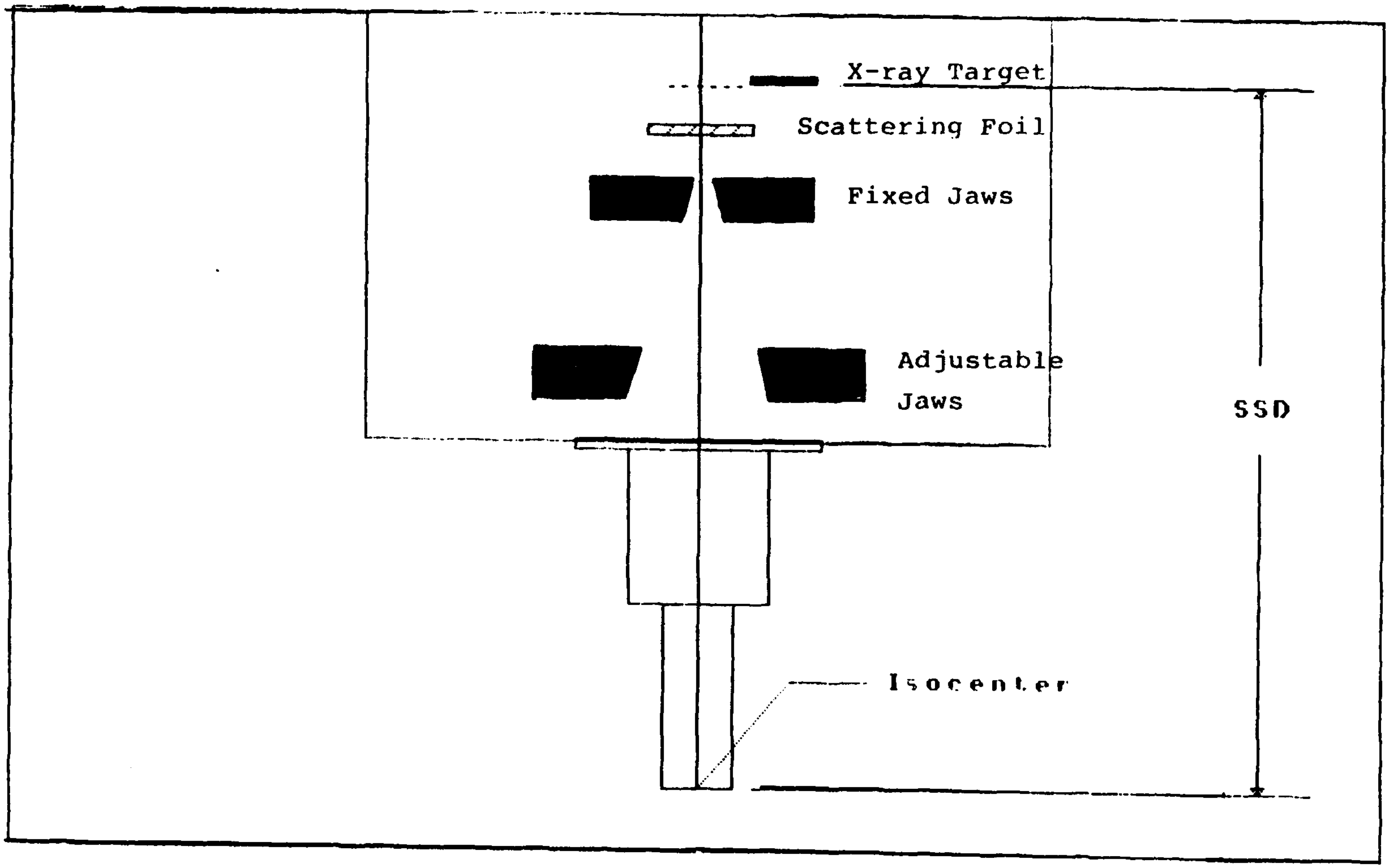

Figure 3 - Electron-Beam Pathway

Mayo Clinic personnel have extensively investigated the effect of aperture size on the dose delivery characteristics of IORT applicators. They recommend setting the variable set of collimators to a 10 cm x 10 cm aperture for IORT applicators with circular cross-sections (5:262-264). It is extremely important to use the same collimator jaw setting for both characterization studies and treatment. A 10 cm x 10 cm aperture is used throughout this study.

IORT Delivery System The IORT delivery system is manufactured by Radiation Products Design. The current design is an improved version of the prototype system that Mayo Clinic developed and reported on in 1982 (5:261-268). The system consists of a docking tube and a set of applicators. A short discussion about each component is required since there is no operating guide associated with the IORT system.

Each IORT applicator consists of a circular tube with a set of spacing rings and a radiation shield at the upper end. Figure 4 identifies the key features of typical IORT applicators.

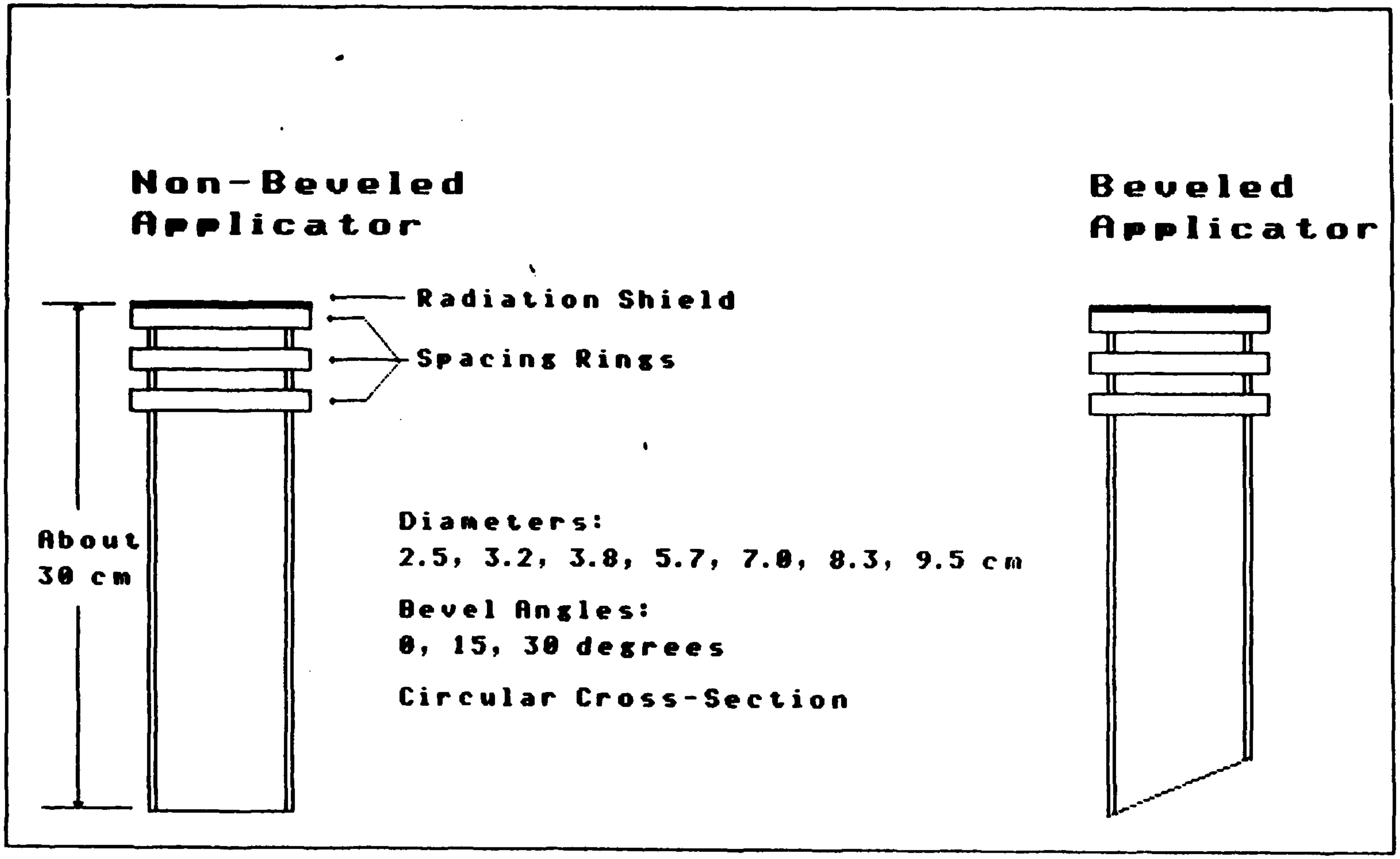

Figure 4 - IORT Applicator (Typical)

The applicator is made from acrylic tubing with a wall thickness of 3.5-mm and an inner diameter of either 2.5-, 3.2-, 3.8-, 5.7-, 7.0-, 8.3-, or 9.5-cm. The applicator is approximately 30-cm long. The end of the applicator can either be flat or beveled. Beveled applicators allow the end of the applicator to lay directly on sloping tissue surfaces. Bevel angles of 15- and 30-degrees are available. The 30-degree applicators are only available in the four larger tube diameters.

Acrylic spacing rings allow each applicator to be docked within the docking tube regardless of the IORT applicator diameter. The outer diameter of the spacing rings is 10.2-cm while the inner diameter of the docking tube is 10.4-cm. Thus, the IORT applicators are designed to slide freely within the docking tube to prevent compression of the patient due to normal respiratory movements.

A radiation shield is attached to the upper end of each IORT applicator. It consists of a chrome-plated brass ring approximately 5-mm thick. The outer diameter of the ring is 10.2-cm with the inner diameter corresponding to the diameter of the tubing. The shield helps reduce radiation leakage through the spacing rings. Without the shield, normal tissue in the periphery might receive an unacceptably large dose.

The docking tube provides a means of mounting an IORT applicator on the treatment head and allowing visualization of the tumor after mounting the applicator. Figure 5 identifies the key features of the docking tube.

The docking tube is constructed from hardened aluminum and is designed to attach to the treatment head of the linear accelerator via the wedge mount. The hinged-door helps speed up the process of docking the applicator. A nylon set-screw may be used to clamp the IORT applicator in place during characterization studies. A retractable mirror and periscope system allows for viewing down the central axis of the IORT applicator.

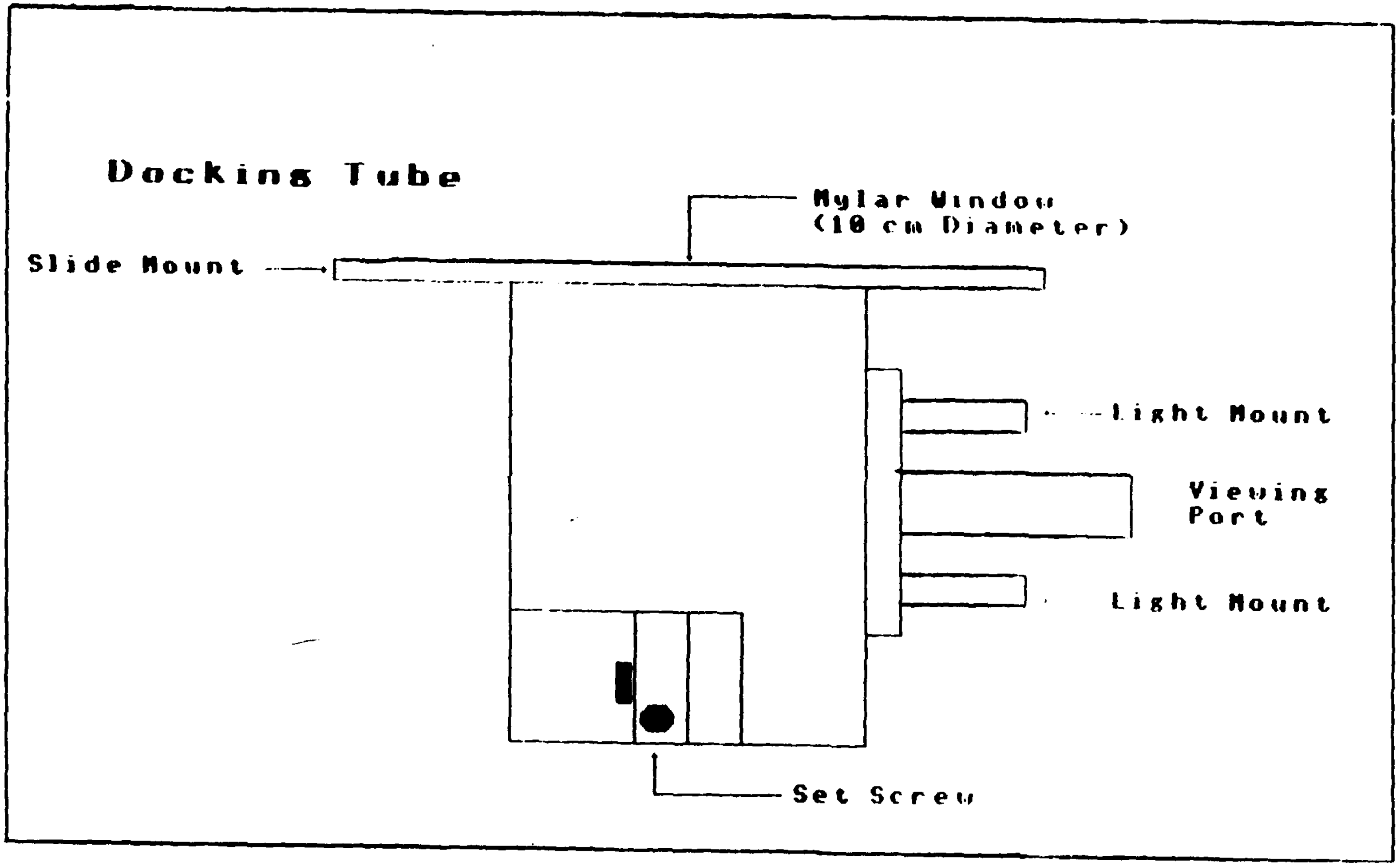

Figure 5 - IORT Docking Tube

III. IORT Characterization

The medical physicist's primary job is to assist the radiation oncologist and surgeon by providing them with a complete description of the dose delivery characteristics for every combination of IORT applicator and electron-beam energy. The characteristics of interest include: isodose charts, output factors, effective SSDs, offset factors, central-axis (CAX) profiles.

Each characteristic is important in the IORT treatment planning process. Isodose charts are used to help select the right combination of IORT applicator and electron-beam energy. Output factors and offset factors are used to scale the prescribed dose to the appropriate number of monitor units (MUs). CAX profiles are used to find the surface dose factors, output factors, and x-ray contamination dose factors.

Radiographic film is used to determine isodose charts, output factors, and CAX profiles. The effective SSDs are determined more precisely by using an ionization chamber and electrometer. An offset factor are calculated by using the appropriate effective SSD and the offset distance of the IORT applicator in the docking tube. This chapter addresses each characteristic in terms of what it is, why it is important, and how it is determined. Sample results are included.

Isodose Charts

An isodose chart shows the variation of absorbed dose in a plane which contains the central axis of the electron-beam. The chart consists of a family of isodose curves which are lines passing through points of equal dose. The curves are drawn at regular intervals of absorbed dose and expressed as a percentage of the maximum dose along the central axis of the electron-beam. The point at which the central axis dose reaches its maximum value is known as dmax.

The scattering of electrons due to the collimation of the beam plays a significant role in determining the shape of the isodose curves (4:314). Since each IORT applicator collimates the beam differently, isodose profiles must be determined for every combination of IORT applicator and electron-beam energy.

Isodose charts help define the treatment region. The treatment region is considered to be that region contained within the 90% isodose curve. By comparing isodose charts for different IORT applicators, the radiation oncologist and surgeon can select the appropriate combination of IORT applicator and electron beam energy. In order to help visualize the dose distribution, the isodose curves are displayed in 5% increments from 90% to 105% and in 10% increments over the range of 10% to 90%. It is helpful to tabulate the depth and width of the 90% isodose profile for quick reference.

The procedures and equipment for determining isodose charts for IORT applicators are nearly identical to those used for EBRT applicators. The only difference is that in the case of a beveled applicator, the gantry must be rotated through an angle equal to the bevel angle. This allows the end of the applicator to rest flat on the surface of the phantom just like it would rest on a tumor during a treatment. The equipment required to determine isodose charts includes radiographic film, a phantom constructed from water-equivalent plastic, a phantom-holder, an automatic film processor, and a scanning densitometer system with a plotter. The steps required to obtain an isodose chart include:

(1) The film and phantom are placed such that the film lays in the yz-plane as shown in Figure 6. A sheet of film is placed within the film cassette. Inscribed reference marks on the top edge of the film cassette permit accurate alignment of the film with respect to the central axis of the electron beam.

(2) The SSD is set to 100 cm using the front pointer plate and a calibrated rod. An SSD of 100 cm places the end of the IORT applicator at the isocenter of gantry rotation.

(3) The gantry is rotated 0- , 15-, or 30-degrees as required to make the end of the IORT applicator lay flat on the surface of the phantom.

(4) The docking tube and IORT applicator are installed. The applicator may be clamped in place by using the nylon set-screw.

(5) The film is irradiated with a dose of 6 MUs. This dose insures the range of ODs on the developed film lay within the range of linear response for Kodak XTL-2 film.

(6) The film is removed from the film cassette and then developed by means of the automatic film processor.

(7) The scanning densitometer system and plotter are used to obtain the isodose chart. The densitometer is zeroed by reading the OD of an unirradiated piece of film. The isodose film is then scanned along its central axis to find maximum OD. This point is used as the normalization point. A scan pattern which covers the region of interest on the film is selected and the scan is started. After completing the scan, the plotter is used to produce the isodose chart.

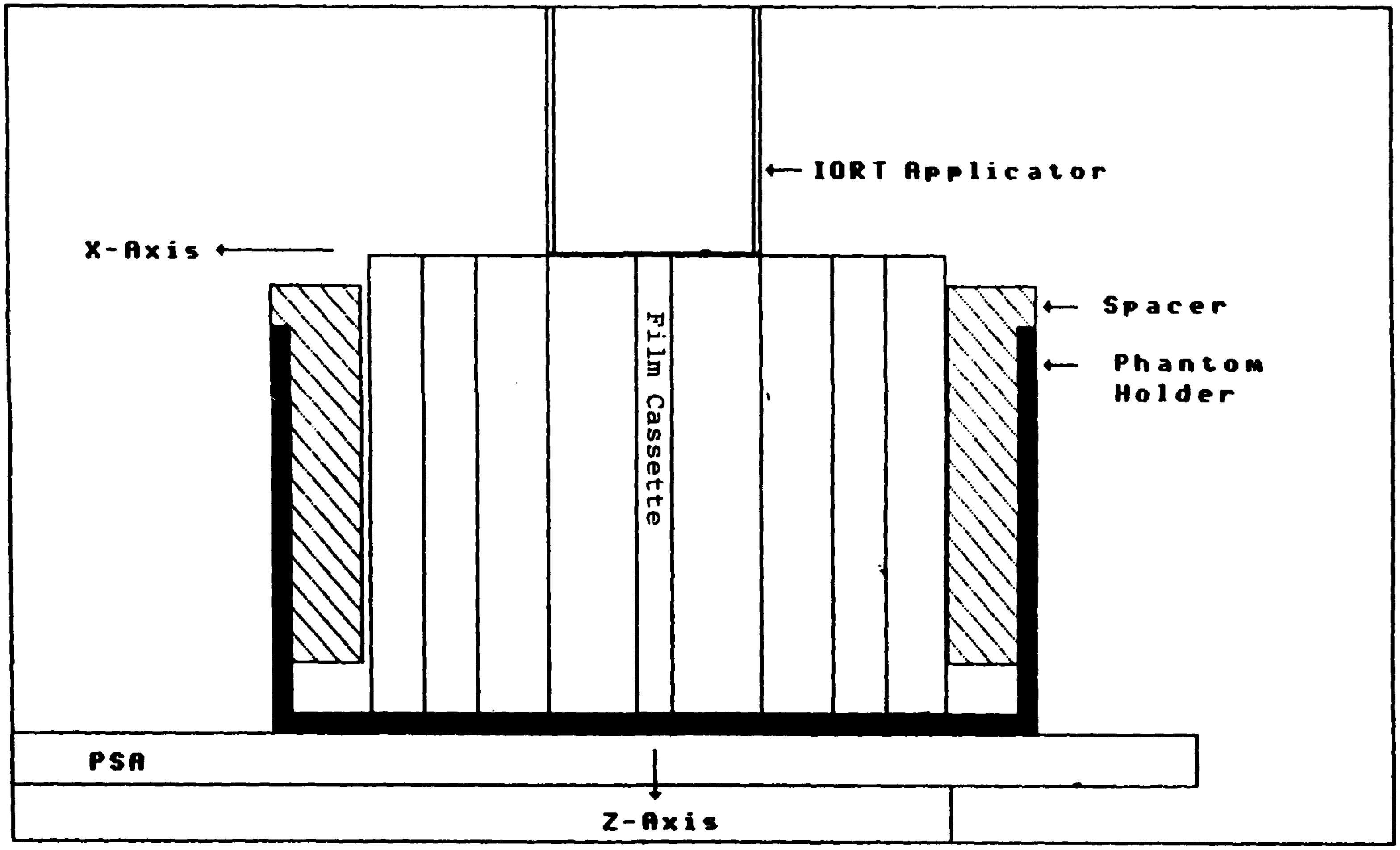

Figure 6 - Obtaining Isodose Films for IORT Characterization

Figures 7, 8 and 9 show the isodose profiles for the 7.0 cm diameter IORT applicator with 0-, 15-, and 30-degree bevel angles, respectively. Each figure shows how the depth and width of the 90% isodose profile are defined.

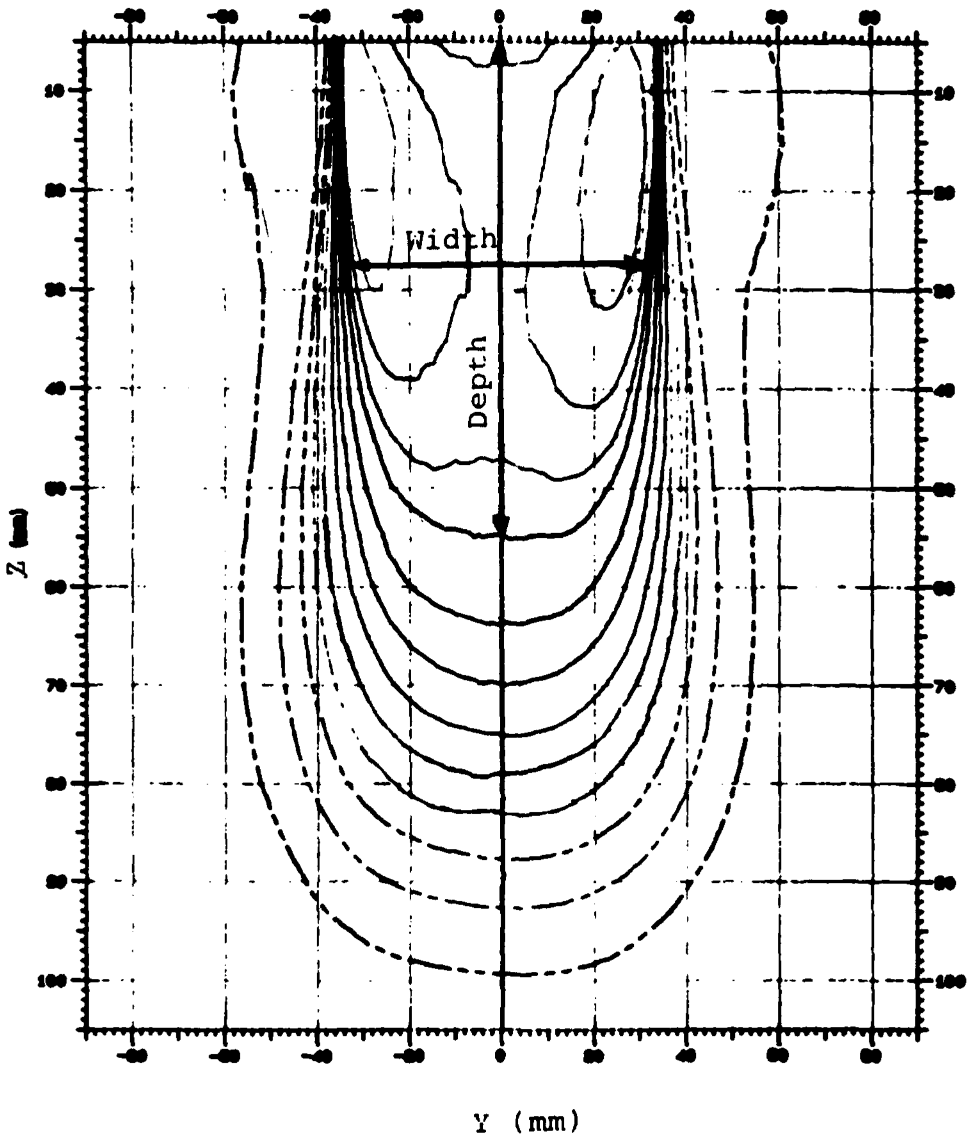

Figure 7 - Typical Isodose Chart: 0-Degree Bevel

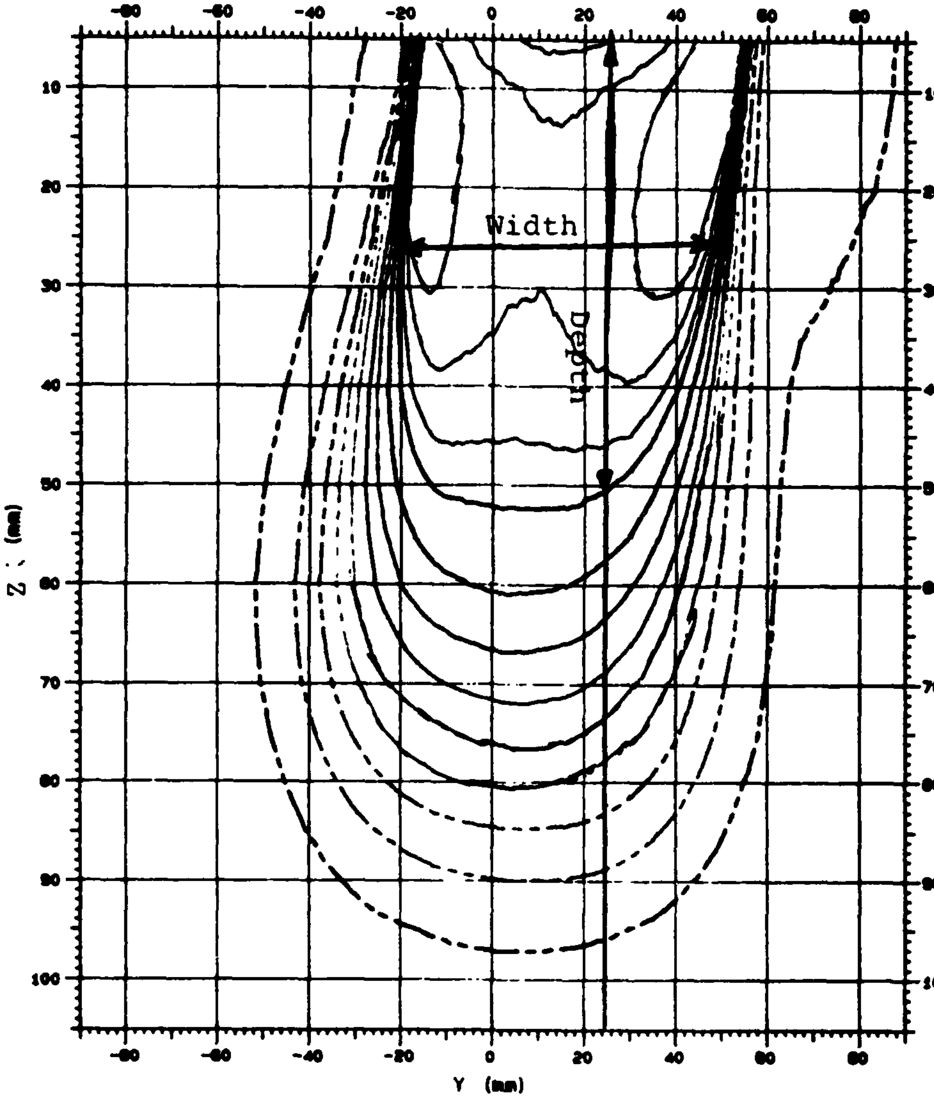

Figure 8 - Typical Isodose Chart: 15-Degree Bevel

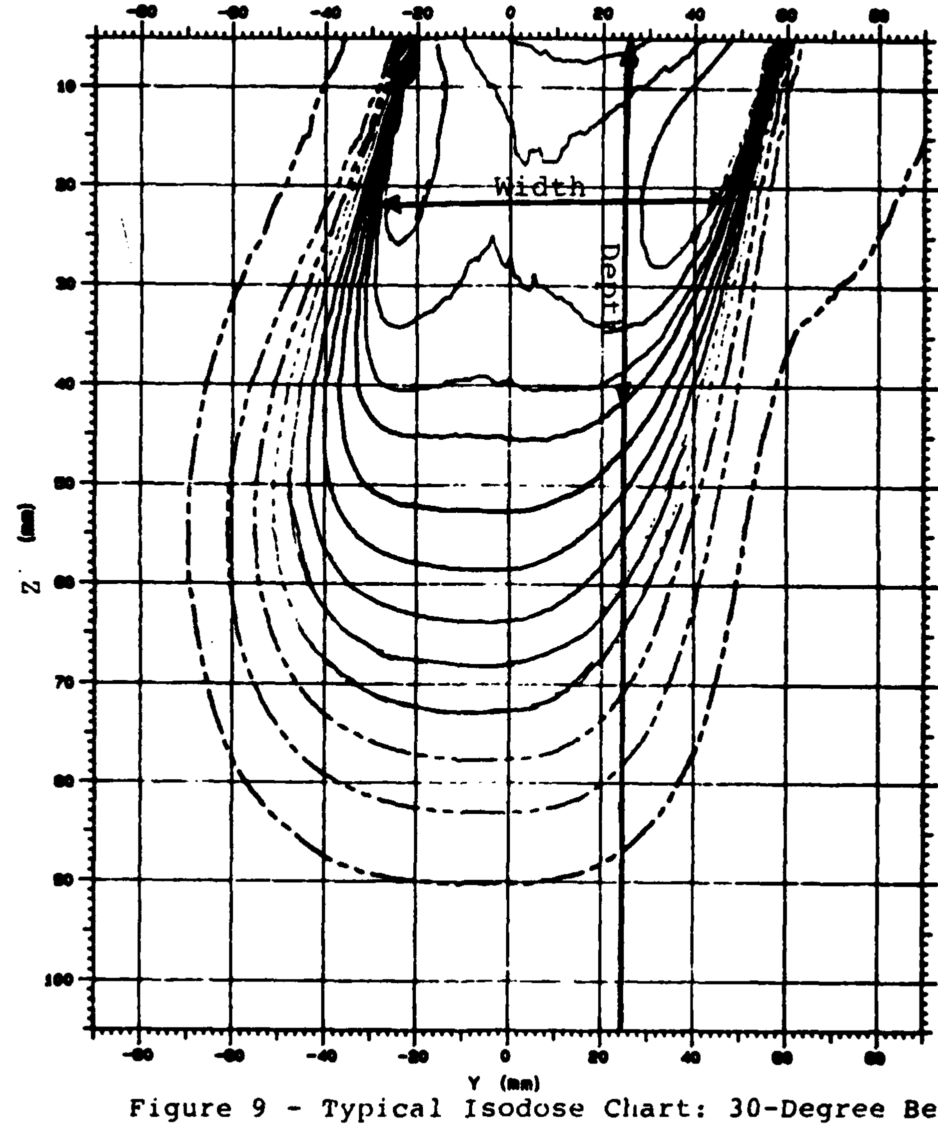

Figure 9 - Typical Isodose Chart: 30-Degree Bevel

Output Factors

The output factor of an IORT applicator is the ratio of the dose delivered per monitor unit (MU) at dmax for the IORT applicator to the dose delivered per MU at dmax for the reference EBRT applicator. Each electron beam is carefully calibrated so the dose in water at dmax equals one centiGray (cGy) per monitor unit (MU) when the reference EBRT applicator and geometry are used. By convention, the reference EBRT applicator is the one which provides a 10 cm x 10 cm field at an SSD of 100 cm.

Output factors are used to calculate the number of MUs required to deliver a specified dose to dmax for an IORT applicator. The number of MUs required to deliver a specified dose is calculated by dividing the specified dose by the Output Factor. If an IORT applicator has an output factor greater than one, it takes fewer MUs to deliver a specified dose to dmax. Conversely, an IORT applicator with an output factor less than one requires more MUs to deliver a specified dose to dmax. A unique output factor exists for every combination of IORT applicator and electron-beam energy.

Output factors are found by using the isodose films and the scanning densitometer. The basic strategy is to determine the ratio of maximum net OD along the central axis of the isodose film for the IORT applicator to that of the "10x10" EBRT applicator. The process for finding the output factor begins by reading the OD for an unirradiated sheet of film to set the background value. The background value is automatically subtracted from all subsequent readings made by the scanning densitometer. The next step is to scan the isodose film for the "10x10" EBRT applicator along its central axis to find its maximum net OD. This value is used to set the normalization point. All subsequent readings made by the scanning densitometer are automatically divided by the maximum net OD along the central axis of the "10x10" EBRT applicator. The final step is to scan along the central axis of the isodose film for the IORT applicator. The maximum value on the central axis profile for the IORT applicator is, by definition, the output factor:

$$Output Factor = \frac{(OD_{dmax} - OD_{Bkg})_{IORT}}{(OD_{dmax} - OD_{Bkg})_{10x10}} \tag{1}$$

Figures 10, 11, 12, and 13 show plots of the output factors for all the IORT applicators for each electron-beam energy. The "humped" shape of the distribution is consistent with the measurements made at Mayo Clinic.

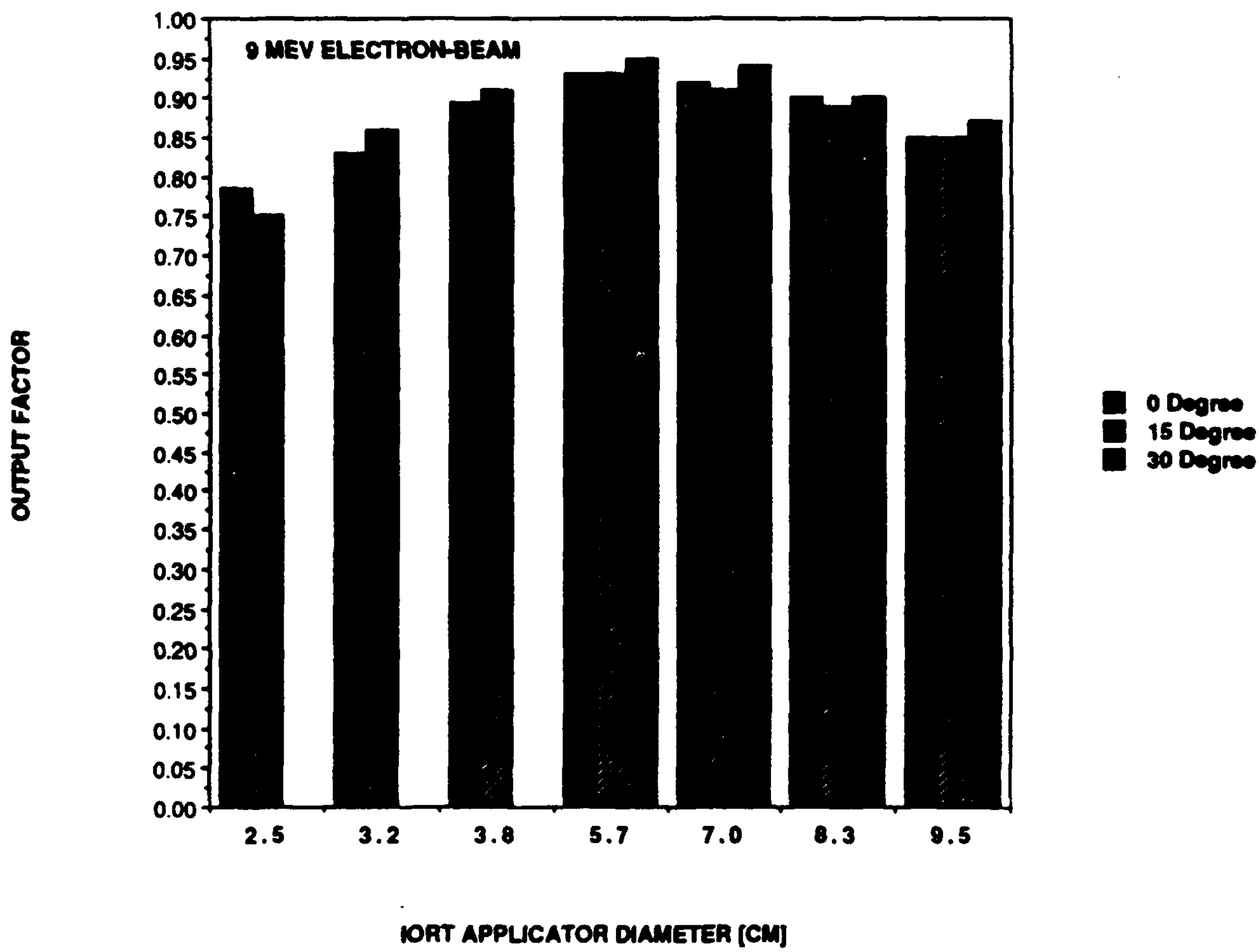

Figure 10 - Output Factors: 9-MeV Electron-Beam

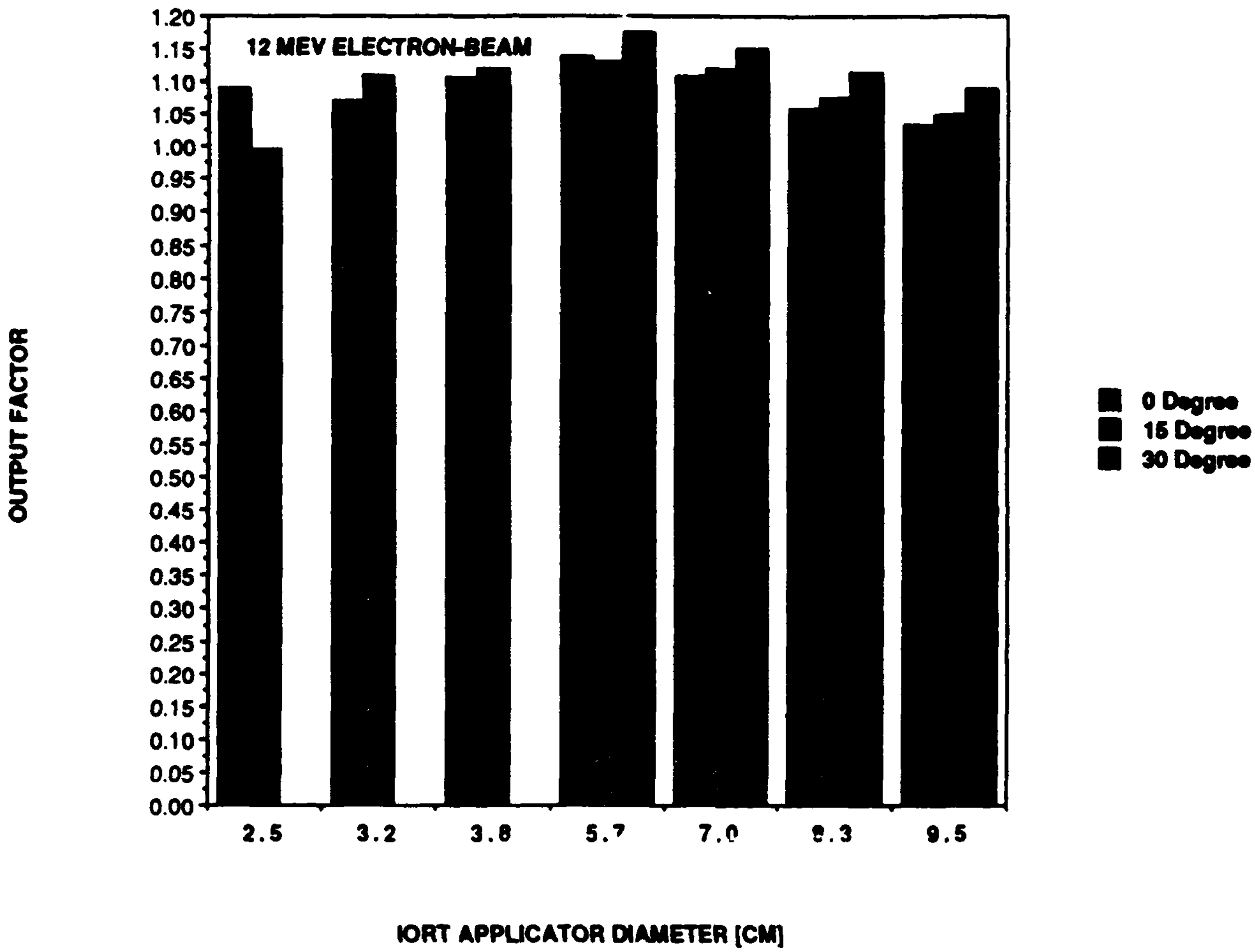

Figure 11 - Output Factors: 12-MeV Electron-Beam

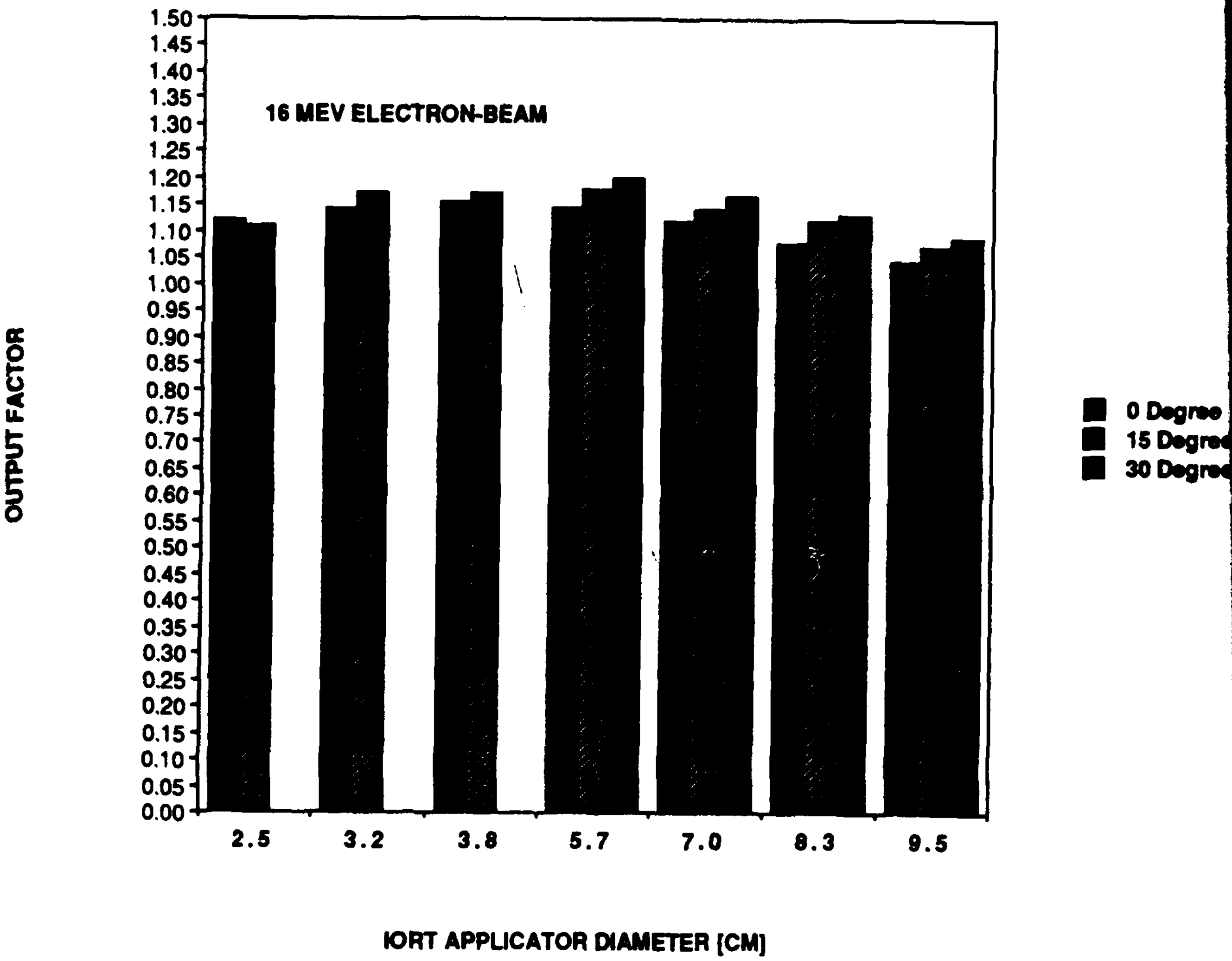

Figure 12 - Output Factors: 16-MeV Electron Beam

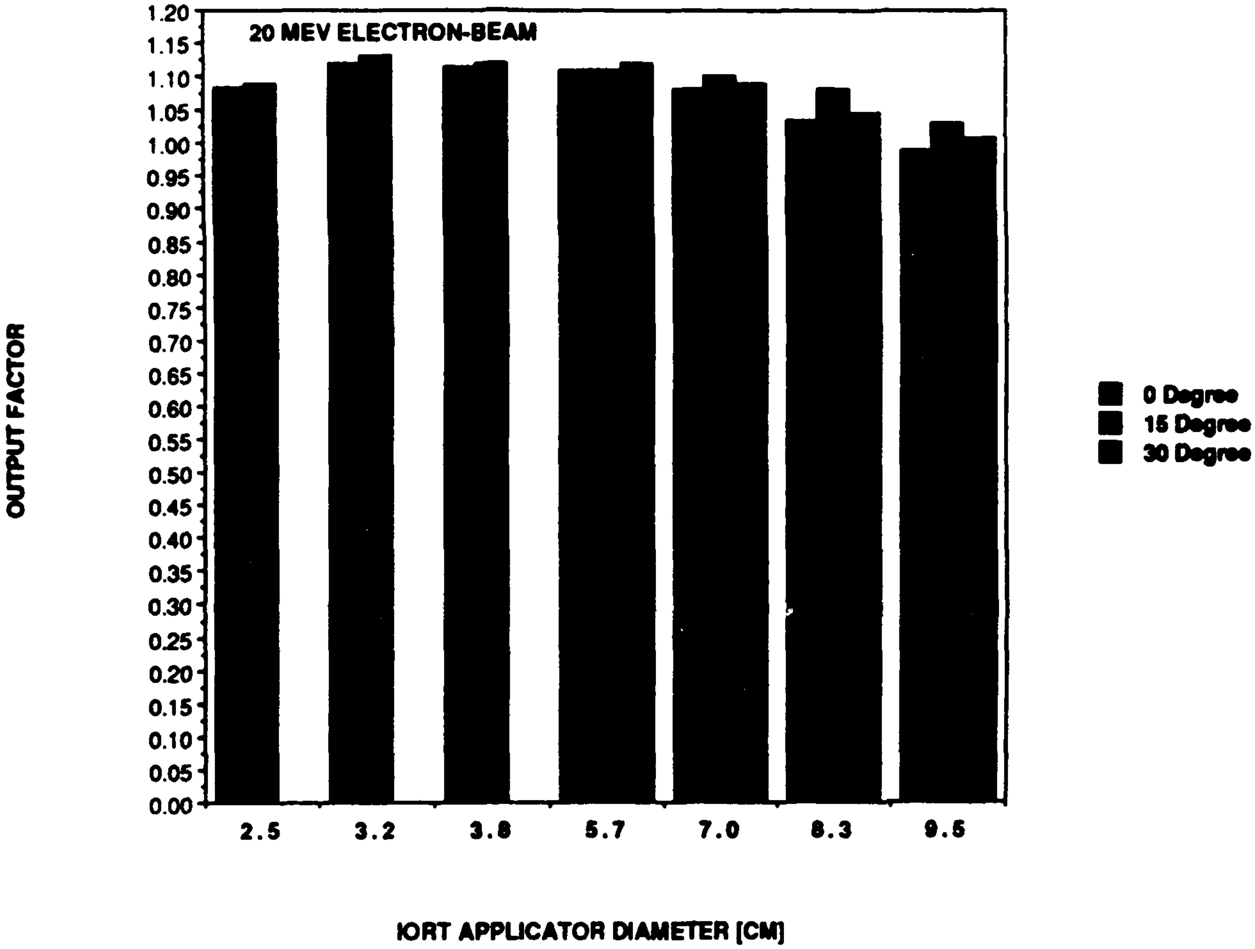

Figure 13 - Output Factors: 20-MeV Electron Beam

Effective SSDs

Since IORT uses electrons, effective Source-to-Surface Distances (SSDs) must be determined. Unlike a photon-beam, an electron-beam does not appear to originate from the location of the x-ray target in the treatment head. This difference is due to the scattering of the electrons from collimator surfaces. As a result, the electron-beam appears to originate from a virtual source. The position of the virtual source is given in terms of the effective SSD. The effective SSD is the distance from the virtual source to the isocenter of gantry rotation. The usefulness of effective SSDs is that they allow the attenuation of the electron-beam to be described by the inverse square law (ISL). The ISL states that the intensity of a point source varies inversely as the square of the distance from the source.

Kahn outlines a method for finding effective SSDs using an ion chamber, a phantom, and an electrometer (4:320-322). A parallel-plate ion chamber and electrometer are used to make a series of measurements of the dose at positions along the central axis. The measurements are made at small distances from the end of the applicator, e.g. every few centimeters up to 10 cm from the end. The first measurement is made with the surface of the phantom in contact with the applicator and the ion chamber at a depth corresponding to dmax within the phantom as shown in Figure 14. A fixed number of MUs is delivered and the electrometer reading (Io) is recorded. After increasing the gap distance (g) by lowering the phantom, the same number of MUs are delivered and the electrometer reading (Ig) is recorded. This data is used to find the effective SSDs based on a plot of $\sqrt{I_o/I_g}$ versus the gap distance.

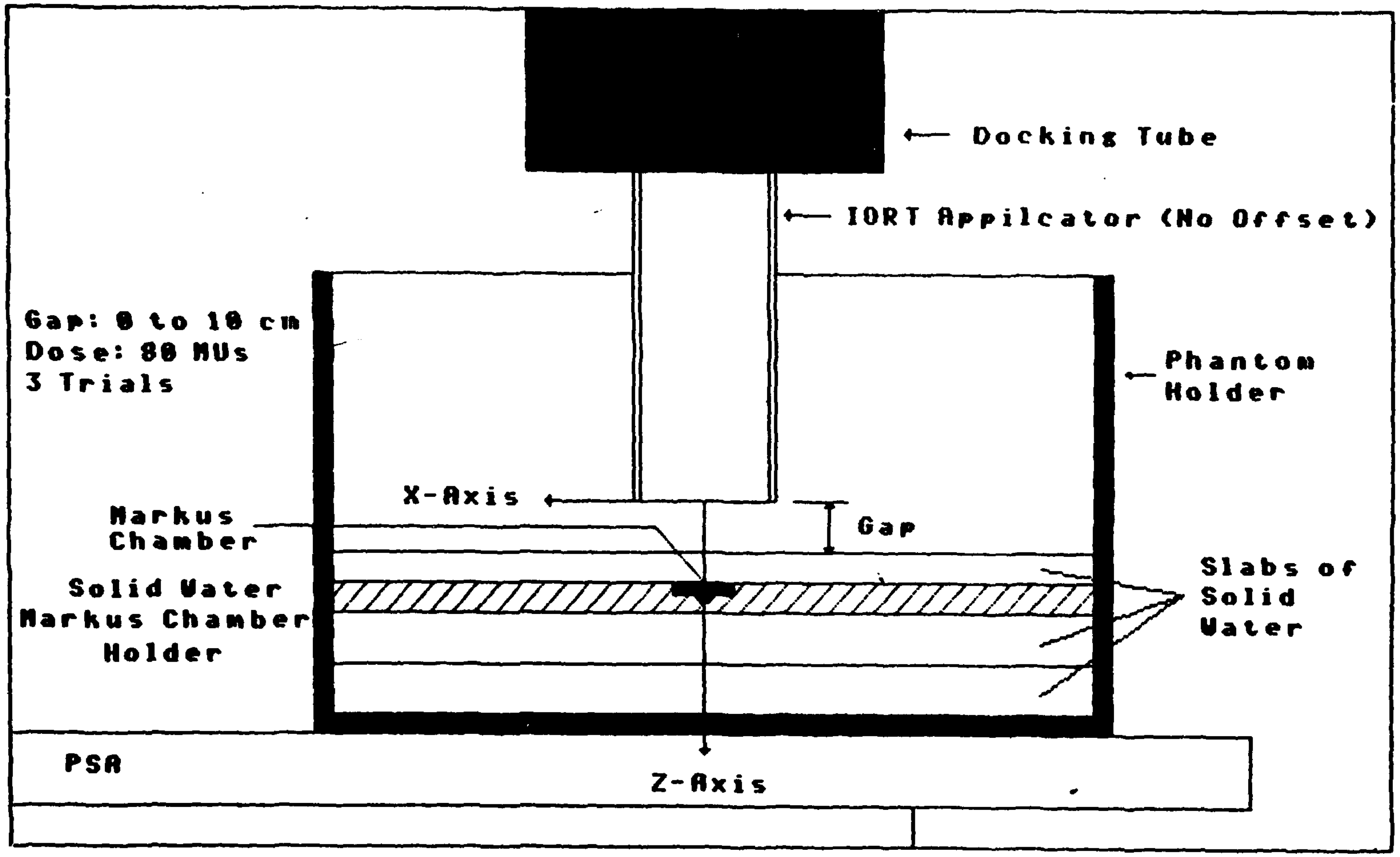

Figure 14 - Equipment Set-Up For Finding Effective SSDs

Kahn asserts that if the electron-beam obeys the inverse square law, then

$$\frac{I_o}{I_g} = \left(\frac{SSD + dmax + g}{SSD + dmax}\right)^2 \qquad (2)$$

or

$$\sqrt{\frac{I_o}{I_g}} = \frac{g}{SSD + dmax} + 1 \qquad (3)$$

A plot of $\sqrt{I_o/I_g}$ versus gap distance will yield a straight line, the slope of which is given by the following expression:

$$Slope = \frac{1}{SSD + dmax} \qquad (4)$$

This equation is then solved for the effective SSD:

$$SSD = \frac{1}{Slope} - dmax \qquad (5)$$

Rather than plotting each data set, it is more efficient to fit the data to a straight line using a least-squares fit. Appendix B contains listings from a LOTUS 1-2-3 worksheet used to record the electrometer readings and calculate the effective SSDs. The slope of the line is found by using the linear-regression-analysis commands which LOTUS 1-2-3 provides.

Table 1 lists the values of effective SSDs as a function of IORT applicator diameter and electron beam energy. It also lists the effective SSDs for the "10x10" EBRT applicator. The significance of effective SSDs is discussed in the next section which concerns offset factors.

Table 1: Effective SSDs [cm]

Applicator Size	20 MeV Beam	16 MeV Beam	12 MeV Beam	9 MeV Beam
"10x10"	82.5	80.9	81.0	76.6
9.5 cm	125.8	123.0	112.1	103.8
8.3 cm	129.8	122.2	113.8	105.0
7.0 cm	124.8	120.5	112.1	99.2
5.7 cm	115.9	118.6	105.1	88.4
3.8 cm	94.2	81.5	69.3	57.4
3.2 cm	79.4	71.0	56.2	47.3
2.5 cm	58.7	57.9	43.6	37.9

Offset Factors

Experience at Mayo Clinic indicates that in a significant number of cases the angle of the accelerator gantry and patient support assembly turntable are such that it is not possible to fully dock the IORT applicator within the docking tube. In such a case, the IORT applicator has either a positive or negative offset. Figure 15 shows each case.

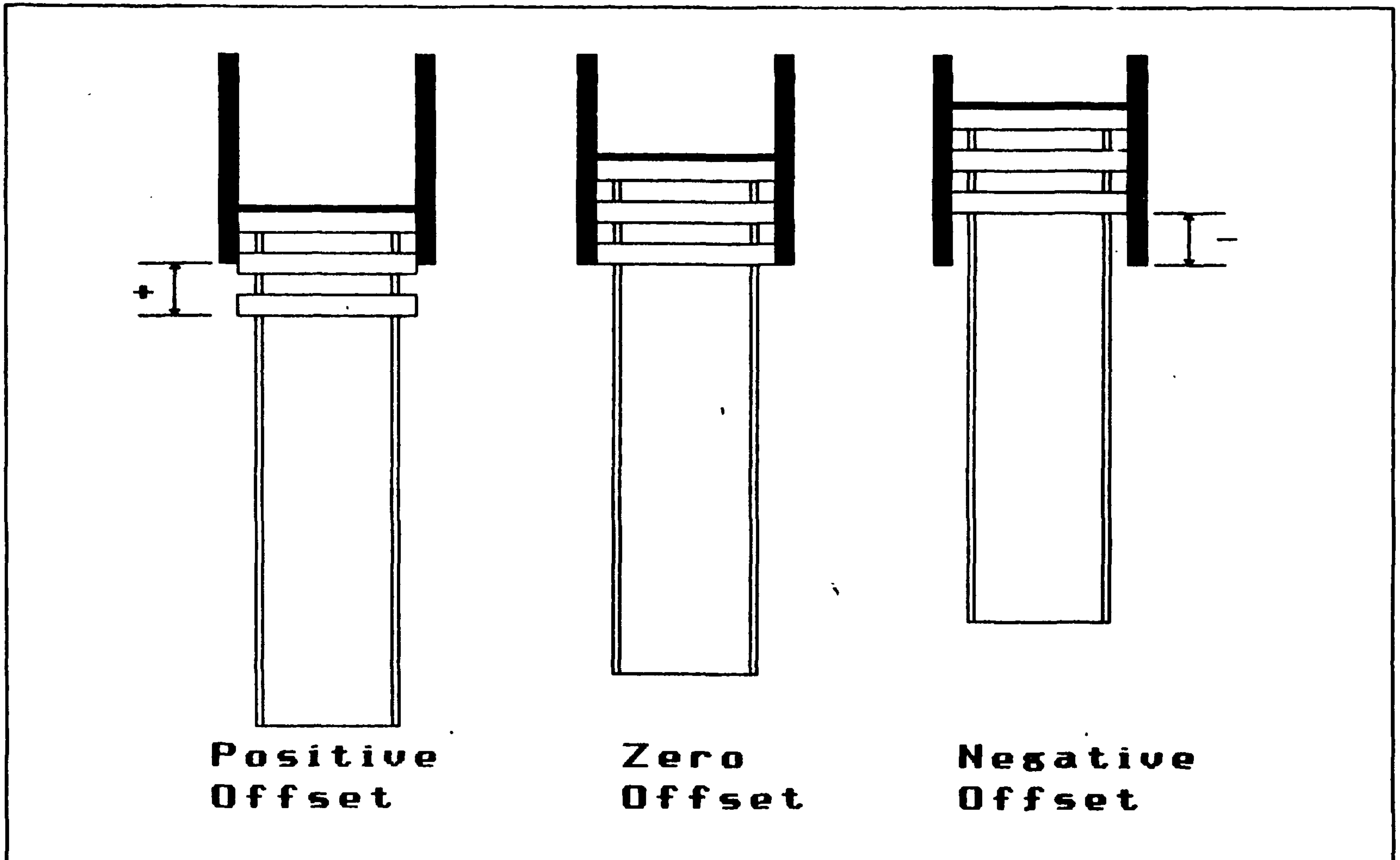

Figure 15 - IORT Offsets: Positive/Zero/Negative

The net effect of an offset is either an increase or decrease in the dose delivered to dmax based on consideration of the inverse-square-law behavior of the electron beam. A positive offset moves the location of dmax further from the virtual source and thereby reduces the dose. A negative offset moves the location of dmax closer and thereby increases the dose. Mayo Clinic defines the Offset Factor as:

$$OffsetFactor = \frac{(EffectiveSSD + Offset)^2}{(EffectiveSSD)^2} \qquad (6)$$

The term "Offset" is the offset distance measured after docking the applicator. The term "Effective SSD" is experimentally-measured and depends on the diameter of the IORT applicator and the electron-beam energy.

Offset factors are used to adjust the calculation of the number of MUs required to deliver a specified dose to dmax for IORT applicator when the IORT applicator is offset. The adjusted number of MUs is given by the product of the offset factor and the number of MUs predicted by the ratio of the specified dose to the output factor.

Central Axis Profiles

A central axis profile is a plot of the relative dose versus depth along the central axis of the IORT applicator. Conventionally, the profile is normalized to the dose at dmax for the applicator in question. In this study, however, the central axis profiles are normalized relative to the dose at dmax for the "10x10" EBRT applicator. This allows determination of the output factor directly from the central axis profile.

The central axis profile provides three important pieces of information: the output factor, the surface dose factor, and the x-ray dose factor. The importance of the output factor is discussed elsewhere. The surface dose factor is needed to calculate the dose delivered to the surface of the tumor. The x-ray dose factor is needed to calculate the dose delivered to the underlying tissue by more penetrating x-ray radiation. The x-ray radiation is produced by interaction of the electron-beam with the IORT radiation shield and the walls of the docking tube.

Central axis profiles are found by using the isodose films and the scanning film densitometer as discussed in the section on finding output factors. The densitometer is set to scan along the central axis from a point corresponding to a depth of 0-mm to a depth where the profile levels out. Since the upper edge of the film is 3-mm below the surface of the phantom, the surface dose factor is found by extrapolating the central axis profile back to zero depth. The x-ray dose factor is equal to the magnitude of the "tail" where the profile levels out. Since the central axis profile is not normalized relative to the dose at dmax for the IORT applicator, it is necessary to divide the surface dose factor and the x-ray dose factor by the output factor.

Figures 16, 17, 18, and 19 show the central axis profiles for the 7.0 cm diameter IORT applicator with a 0-degree bevel angle and electron-beam energies of 9-,12-, 16- and 20-MeV, respectively. The normalized surface dose factors ranged from 78% to 92% for the IORT applicators and electron-beam energies considered in this study. The normalized x-ray dose factors ranged from 2% to 5% for the IORT applicators ans electron-beam energies considered in this study.

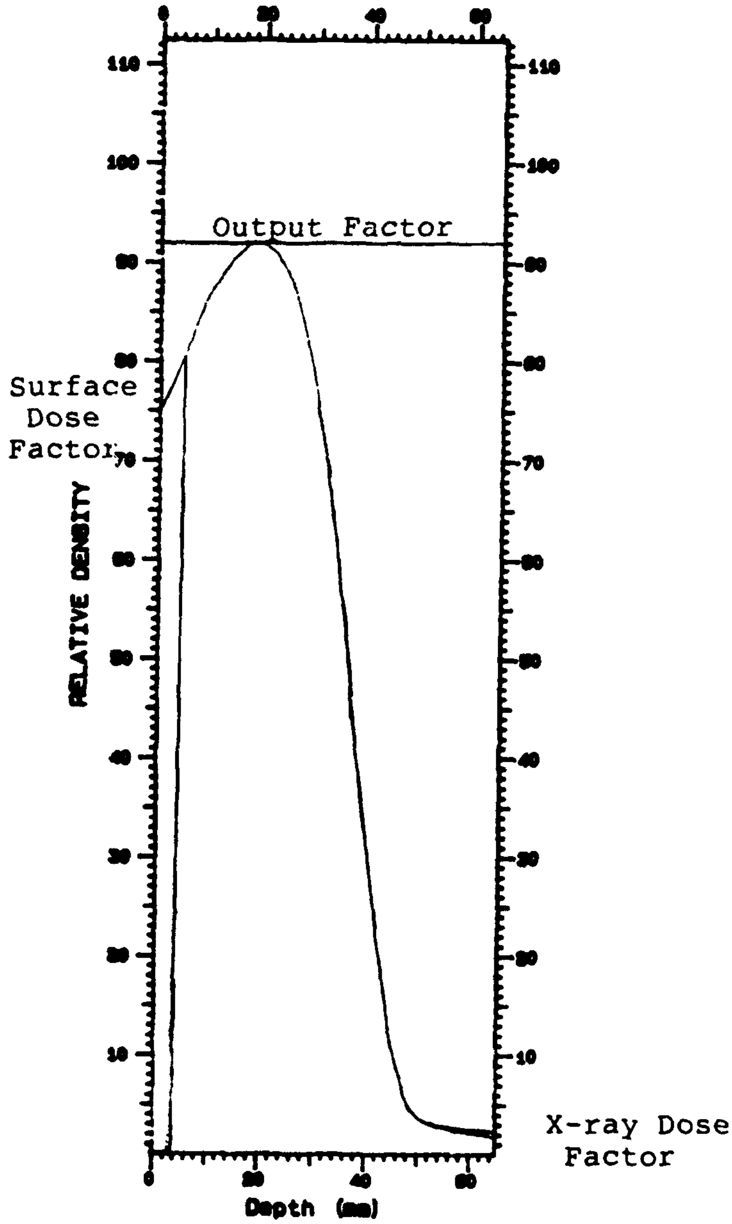

Figure 16 - Central Axis Profile:9-MeV Electron-Beam

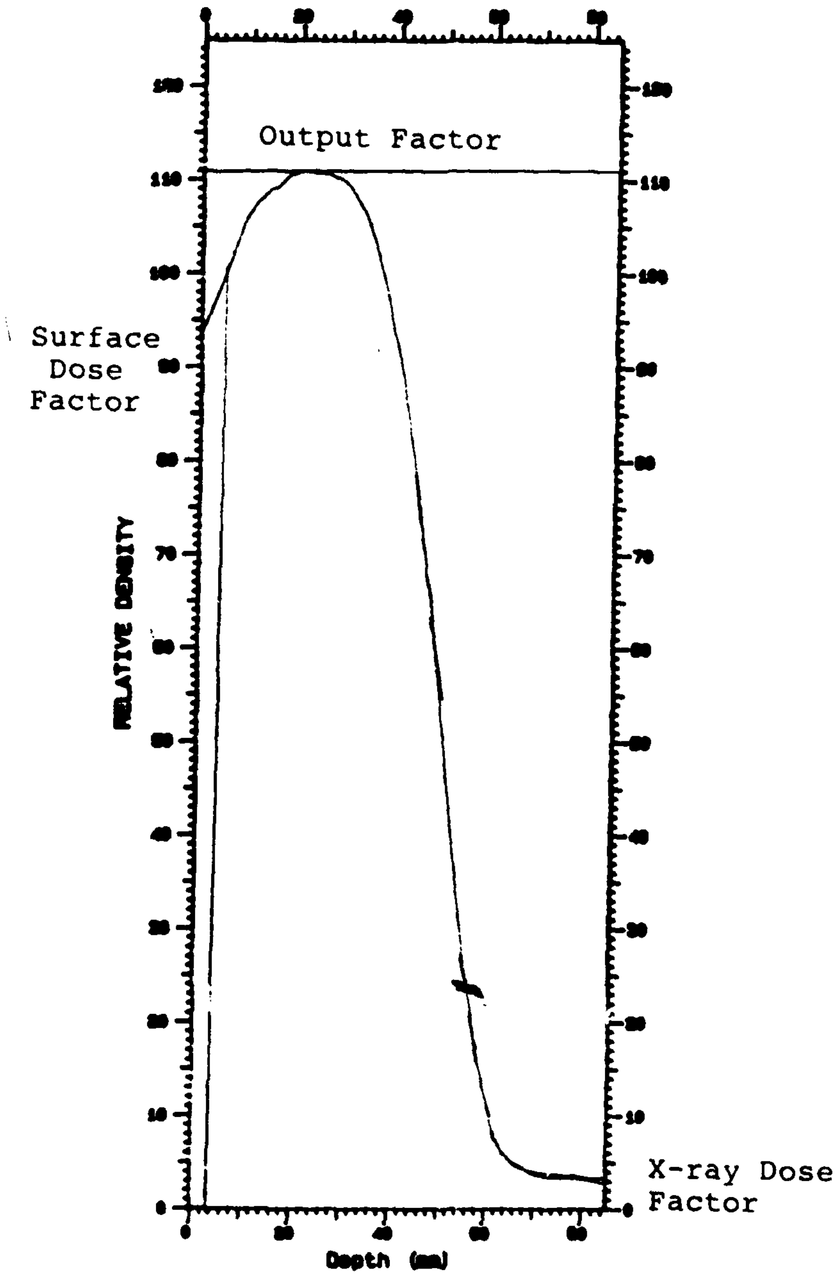

Figure 17 - Central Axis Profile: 12-MeV Electron-Beam

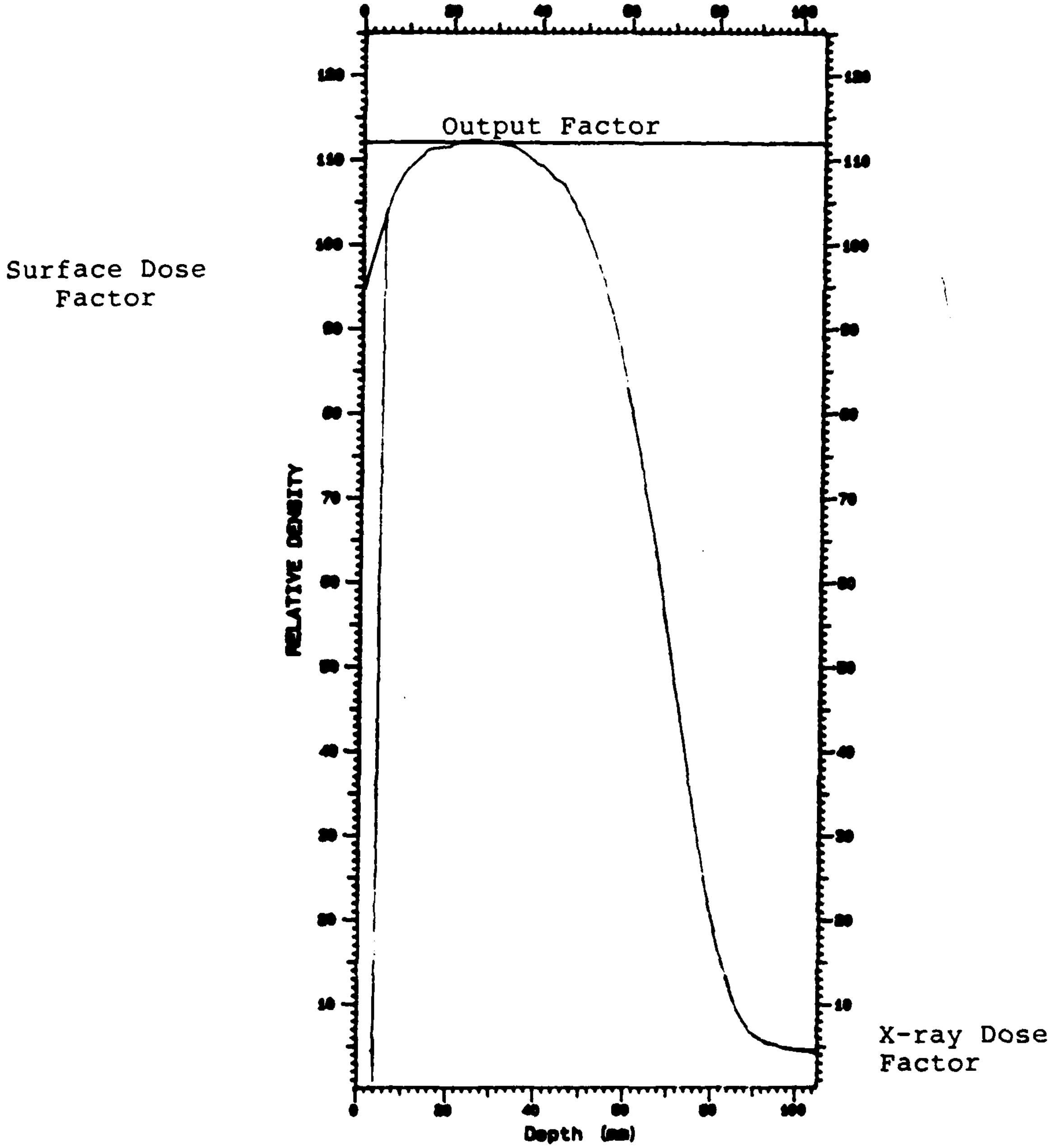

Figure 18 - Central Axis Profile: 16-MeV Electron-Beam

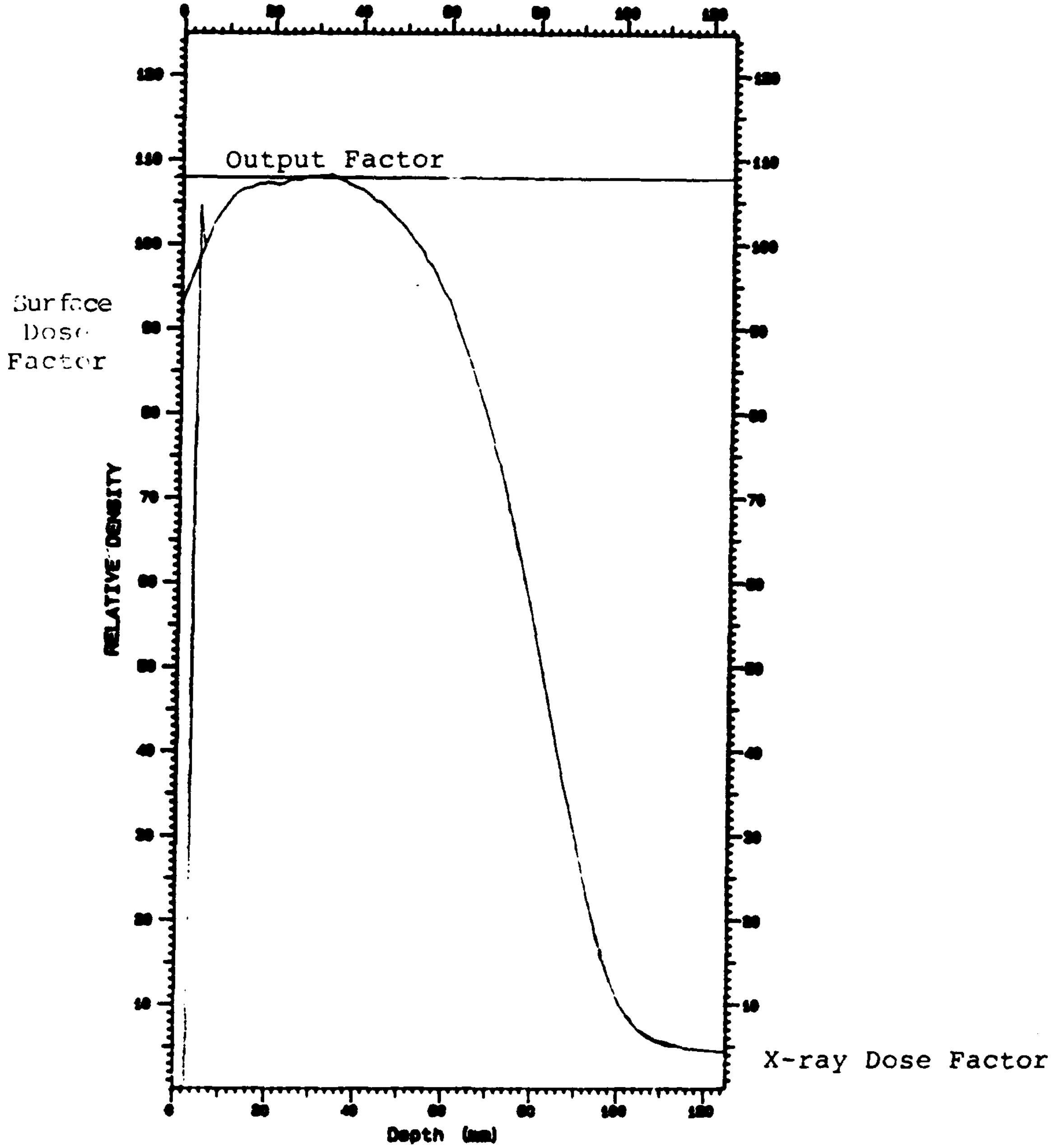

Figure 19 - Central Axis Profile: 20-MeV Electron-Beam

IV. Treatment Planning

IORT treatment planning is a "real-time" process. Almost every decision must be made at the time of treatment. After the tumor is surgically exposed, the radiation oncologist and surgeon define the treatment region. They must then select the right combination of IORT applicator and electron-beam energy. The isodose charts are consulted to find the combination such that the treatment site is contained within the 90% isodose curve. In the case of a large treatment site, a series of abutted placements may be needed. It may be necessary to either move or shield radiosensitive normal tissue in the periphery. The IORT applicator is positioned in the patient and then the PSA and gantry are maneuvered until the IORT applicator is docked in the docking tube. After measuring the offset distance, the effective SSD, and the output factor are looked up in a table. With these figures and a prescribed dose, the medical physicist can calculate the number of MUs, the surface dose and x-ray dose.

Determining Number of Monitor Units

The number of MUs required to deliver a prescribed dose to the 90% isodose curve is equal to

$$MonitorUnits = \frac{(PrescribedDose)(OffsetFactor)}{(0.90)(OutputFactor)} \qquad (7)$$

"Prescribed Dose" is the dose to be delivered to 90% isodose profile. The factor of 0.90 is necessary since the dose is specified to the 90% isodose level rather than to dmax. "Offset Factor" is calculated from Equation 6 by using the appropriate effective SSD from Table 1. "Output Factor" is the output factor for the particular combination of IORT applicator and electron-beam energy.

Determining Surface Dose

The surface dose is equal to

$$SurfaceDose = \frac{(SurfaceDoseFactor)(PrescribedDose)}{(0.90)} \quad (8)$$

Determining X-ray Dose

The x-ray dose is equal to

$$X-rayDose = \frac{(X-rayDoseFactor)(PrescribedDose)}{(0.90)} \quad (9)$$

Estimating Dose Uncertainty.

The radiation oncologist will tolerate an uncertainty of +/- 5% in the delivered dose. In principle, the uncertainty in the dose depends on the uncertainties in the calibration factor, output factor, and offset factor. In actuality, it depends on the uncertainties in the calibration factor and the output factor.

The dose delivered by the accelerator equals

$$Dose = (CalibrationFactor)(MUs) \qquad (10)$$

The calibration factor gives the dose per MU delivered to dmax using the "10x10" EBRT applicator. Its value is equal to 1 rad/MU +/- 3%. The uncertainty in dose is given by

$$\frac{\sigma_{Dose}}{Dose} = \sqrt{\left(\frac{\sigma_{MUs}}{MUs}\right)^2 + \left(\frac{\sigma_{CalibrationFactor}}{CalibrationFactor}\right)^2} \qquad (11)$$

Since the maximum allowable uncertainty equals +/- 5% and the uncertainty in the calibration factor is +/- 3%, the maximum allowable uncertainty in the number of MUs is +/- 4%. In reality, the maximum allowable uncertainty in the number of MUs translates into a maximum allowable uncertainty of +/- 4% in the output factor since the offset factor is very precisely known.

The output factor is given by

$$Output\,Factor = \frac{(OD_{dmax} - OD_{Bkg})_{IORT}}{(OD_{dmax} - OD_{Bkg})_{10x10}} \qquad (12)$$

The uncertainty in the output factor is approximately equal to

$$\frac{\sigma_{Output\,Factor}}{Output\,Factor} = \sqrt{2}\frac{\sigma_{OD}}{OD} \qquad (13)$$

Since the uncertainty in OD is +/- 2%, the uncertainty in the output factor is equal to +/- 2.8%. This means the uncertainty in the dose is less than the +/- 5% goal set by the radiation oncologist.

V. Conclusions and Recommendations

Conclusions

As a result of this study, a complete catalog of isodose profiles, output factors, effective SSDs, offset factors, and central axis profiles is available for use by the medical physicists and radiation oncologists at the USAF Medical Center.

The approach outlined in this report provides for a clinically-acceptable uncertainty in delivered dose. The uncertainty in dose is less than the goal of 5%.

The most significant contribution of this report is the recognition of the variation of effective SSDs as a function of IORT applicator diameter and electron beam energy. The effective SSD is used to calculate the offset factor which in turn is used to convert a prescribed dose into the appropriate number of MUs. If the effective SSD for the "10x10" EBRT applicator is used rather than the effective SSD for the IORT applicator, significant errors are possible.

Recommendations

All of the measurements to determine the output factors should be repeated using film for verification purposes. The output factors for the non-beveled applicators should be measured with an ionization chamber in water for purposes of comparison.

The acquisition of elliptical IORT applicators is highly recommended. Mayo Clinic has found them indispensable for treatment sites in the pelvic region. Reference 6 serves as a guide for picking the appropriate sizes and angles.

An "IORT plug" should be fabricated to set the collimator jaws to the required 10 cm x 10 cm aperture. The necessary parts are available from Varian. This will help eliminate errors due to improper aperture size.

Appendix A: Characteristic Curves

The characteristic curve relates the opacity of the developed film to the dose delivered to the film. Opacity is defined as Io/I, where Io is the light intensity measured in the absence of the film, and I is the intensity transmitted through the film in a direction perpendicular to its plane (1:412-414). Because of the tremendous range of values for opacity, it is convenient to define the optical density (OD) as

$$OD = \log\left(\frac{Io}{I}\right) \tag{14}$$

The lower limit of film response, denoted by (OD)min, is found by developing an unirradiated sheet of film. The upper limit of film response, denoted by (OD)max, is found by developing a saturated sheet of film. Saturation is achieved by exposing the film to a strong light. It is convenient to define the standard density (SD) as

$$SD = \frac{(OD)-(OD)\mathrm{min}}{(OD)\mathrm{max}-(OD)\mathrm{min}} \tag{15}$$

Appendix B: Effective SSD Data

Effective SSD Worksheet

Reference: The Physics of Radiation Therapy by Kahn

PRM Dosimeter   80 MUs @ 240 MUs/Minute
Markus Chamber
Solid-Water Phantom

Units: I1,I2,I3 (I) [nC]
       Depth,SSD,Gap [cm]

10 x 10 Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	Eff SSD
20 MeV	2.0	98	0	1.765	1.766	1.765	1.7653	0.0006	1.0000	0.0005	1.0000	
		100	2	1.687	1.689	1.693	1.6897	0.0031	1.0448	0.0019	1.0221	
		102	4	1.617	1.616	1.619	1.6173	0.0015	1.0915	0.0011	1.0448	
		104	6	1.543	1.553	1.543	1.5463	0.0058	1.1416	0.0043	1.0685	
		106	8	1.475	1.479	1.483	1.4790	0.0040	1.1936	0.0033	1.0925	
		108	10	1.411	1.409	1.412	1.4107	0.0015	1.2514	0.0014	1.1187	
		110	12	1.360	1.352	1.358	1.3567	0.0042	1.3012	0.0040	1.1407	82.5 cm
16 MeV	2.0	98	0	1.764	1.764	1.767	1.7650	0.0017	1.0000	0.0014	1.0000	
		100	2	1.691	1.689	1.685	1.6883	0.0031	1.0454	0.0022	1.0225	
		102	4	1.610	1.607	1.608	1.6083	0.0015	1.0974	0.0015	1.0476	
		104	6	1.539	1.536	1.548	1.5410	0.0062	1.1454	0.0048	1.0702	
		106	8	1.472	1.474	1.473	1.4730	0.0010	1.1982	0.0014	1.0946	
		108	10	1.404	1.403	1.405	1.4040	0.0010	1.2571	0.0015	1.1212	
		110	12	1.345	1.352	1.352	1.3497	0.0040	1.3077	0.0041	1.1436	80.9 cm
12 MeV	2.0	98	0	1.669	1.663	1.665	1.6657	0.0031	1.0000	0.0026	1.0000	
		100	2	1.590	1.590	1.587	1.5890	0.0017	1.0482	0.0022	1.0238	
		102	4	1.514	1.517	1.512	1.5143	0.0025	1.0999	0.0027	1.0488	
		104	6	1.449	1.451	1.453	1.4510	0.0020	1.1479	0.0026	1.0714	
		106	8	1.384	1.385	1.383	1.3840	0.0010	1.2035	0.0024	1.0970	
		108	10	1.326	1.326	1.323	1.3250	0.0017	1.2571	0.0028	1.1212	
		110	12	1.274	1.271	1.273	1.2727	0.0015	1.3088	0.0029	1.1440	81.0 cm
9 MeV	2.0	98	0	1.598	1.598	1.601	1.5990	0.0017	1.0000	0.0015	1.0000	
		100	2	1.521	1.518	1.519	1.5193	0.0015	1.0524	0.0016	1.0259	
		102	4	1.450	1.450	1.443	1.4477	0.0040	1.1045	0.0033	1.0510	
		104	6	1.381	1.379	1.385	1.3817	0.0031	1.1573	0.0028	1.0758	
		106	8	1.321	1.321	1.320	1.3207	0.0006	1.2108	0.0014	1.1003	
		108	10	1.258	1.258	1.258	1.2580	0.0000	1.2711	0.0014	1.1274	
		110	12	1.202	1.201	1.203	1.2020	0.0010	1.3303	0.0018	1.1534	76.6 cm

9.5/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.794	1.795	1.792	1.7937	0.0015	1.0000	0.0012	1.0000	
		102	2	1.744	1.744	1.745	1.7443	0.0006	1.0283	0.0009	1.0140	
		104	4	1.695	1.696	1.695	1.6953	0.0006	1.0580	0.0010	1.0286	
		106	6	1.641	1.645	1.643	1.6430	0.0020	1.0917	0.0016	1.0448	
		108	8	1.590	1.592	1.592	1.5913	0.0012	1.1271	0.0013	1.0617	
		110	10	1.546	1.543	1.544	1.5443	0.0015	1.1615	0.0015	1.0777	125.8 cm
16 MeV	2.0	100	0	1.804	1.803	1.805	1.8040	0.0010	1.0000	0.0008	1.0000	
		102	2	1.753	1.754	1.755	1.7540	0.0010	1.0285	0.0008	1.0142	
		104	4	1.699	1.699	1.700	1.6993	0.0006	1.0616	0.0007	1.0303	
		106	6	1.649	1.649	1.650	1.6493	0.0006	1.0938	0.0007	1.0458	
		108	8	1.599	1.599	1.598	1.5987	0.0006	1.1284	0.0007	1.0623	
		110	10	1.548	1.546	1.546	1.5467	0.0012	1.1664	0.0011	1.0800	123.0 cm
12 MeV	2.0	100	0	1.669	1.668	1.666	1.6677	0.0015	1.0000	0.0013	1.0000	
		102	2	1.612	1.610	1.613	1.6117	0.0015	1.0347	0.0014	1.0172	
		104	4	1.562	1.560	1.559	1.5603	0.0015	1.0688	0.0014	1.0338	
		106	6	1.509	1.509	1.510	1.5093	0.0006	1.1049	0.0011	1.0511	
		108	8	1.457	1.459	1.460	1.4587	0.0015	1.1433	0.0016	1.0692	
		110	10	1.411	1.408	1.407	1.4087	0.0021	1.1839	0.0021	1.0881	112.1 cm
9 MeV	2.0	100	0	1.348	1.347	1.349	1.3480	0.0010	1.0000	0.0010	1.0000	
		102	2	1.298	1.298	1.299	1.2983	0.0006	1.0383	0.0009	1.0189	
		104	4	1.252	1.250	1.253	1.2517	0.0015	1.0770	0.0015	1.0378	
		106	6	1.208	1.206	1.208	1.2073	0.0012	1.1165	0.0014	1.0567	
		108	8	1.165	1.165	1.167	1.1657	0.0012	1.1564	0.0014	1.0754	
		110	10	1.125	1.125	1.125	1.1250	0.0000	1.1982	0.0009	1.0946	103.8 cm

8.3/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.877	1.873	1.875	1.875	0.0020	1.0000	0.0015	1.0000	
		102	2	1.819	1.815	1.817	1.817	0.0020	1.0319	0.0016	1.0158	
		104	4	1.765	1.764	1.767	1.765	0.0015	1.0621	0.0015	1.0306	
		106	6	1.715	1.716	1.717	1.716	0.0010	1.0927	0.0013	1.0453	
		108	8	1.665	1.667	1.670	1.667	0.0025	1.1246	0.0021	1.0604	
		110	10	1.616	1.619	1.619	1.618	0.0017	1.1588	0.0018	1.0765	129.8 cm
16 MeV	2.0	100	0	1.881	1.884	1.887	1.884	0.0030	1.0000	0.0023	1.0000	
		102	2	1.823	1.826	1.826	1.825	0.0017	1.0323	0.0019	1.0160	
		104	4	1.774	1.775	1.775	1.775	0.0006	1.0616	0.0017	1.0303	
		106	6	1.719	1.718	1.721	1.719	0.0015	1.0958	0.0020	1.0468	
		108	8	1.662	1.665	1.665	1.664	0.0017	1.1322	0.0022	1.0641	
		110	10	1.612	1.614	1.614	1.613	0.0012	1.1678	0.0020	1.0806	122.2 cm
12 MeV	2.0	100	0	1.735	1.734	1.735	1.735	0.0006	1.0000	0.0005	1.0000	
		102	2	1.679	1.676	1.679	1.678	0.0017	1.0338	0.0011	1.0167	
		104	4	1.627	1.625	1.629	1.627	0.0020	1.0662	0.0014	1.0326	
		106	6	1.576	1.575	1.576	1.576	0.0006	1.1009	0.0005	1.0492	
		108	8	1.521	1.523	1.522	1.522	0.0010	1.1397	0.0008	1.0676	
		110	10	1.466	1.469	1.469	1.468	0.0017	1.1817	0.0014	1.0870	113.8 cm
9 MeV	2.0	100	0	1.393	1.393	1.393	1.393	0.0000	1.0000	0.0000	1.0000	
		102	2	1.341	1.341	1.343	1.342	0.0012	1.0383	0.0009	1.0190	
		104	4	1.297	1.297	1.296	1.297	0.0006	1.0743	0.0005	1.0365	
		106	6	1.249	1.253	1.253	1.252	0.0023	1.1129	0.0021	1.0549	
		108	8	1.206	1.209	1.208	1.208	0.0015	1.1535	0.0015	1.0740	
		110	10	1.163	1.165	1.163	1.164	0.0012	1.1971	0.0012	1.0941	105.0 cm

7.0/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.940	1.939	1.943	1.9407	0.0021	1.0000	0.0015	1.0000	
		102	2	1.882	1.887	1.885	1.8847	0.0025	1.0297	0.0018	1.0147	
		104	4	1.832	1.835	1.833	1.8333	0.0015	1.0585	0.0014	1.0289	
		106	6	1.776	1.778	1.784	1.7793	0.0042	1.0907	0.0028	1.0444	
		108	8	1.720	1.724	1.723	1.7223	0.0021	1.1268	0.0018	1.0615	
		110	10	1.667	1.668	1.663	1.6660	0.0026	1.1649	0.0022	1.0793	124.8 cm
16 MeV	2.0	100	0	1.945	1.945	1.943	1.9443	0.0012	1.0000	0.0008	1.0000	
		102	2	1.885	1.890	1.890	1.8883	0.0029	1.0297	0.0017	1.0147	
		104	4	1.836	1.833	1.835	1.8347	0.0015	1.0598	0.0011	1.0295	
		106	6	1.779	1.778	1.778	1.7783	0.0006	1.0933	0.0007	1.0456	
		108	8	1.719	1.722	1.721	1.7207	0.0015	1.1300	0.0012	1.0630	
		110	10	1.659	1.663	1.660	1.6607	0.0021	1.1708	0.0016	1.0820	120.5 cm
12 MeV	2.0	100	0	1.784	1.784	1.785	1.7843	0.0006	1.0000	0.0005	1.0000	
		102	2	1.727	1.730	1.729	1.7287	0.0015	1.0322	0.0010	1.0160	
		104	4	1.674	1.678	1.675	1.6757	0.0021	1.0648	0.0014	1.0319	
		106	6	1.622	1.620	1.619	1.6203	0.0015	1.1012	0.0011	1.0494	
		108	8	1.566	1.566	1.565	1.5657	0.0006	1.1397	0.0006	1.0676	
		110	10	1.506	1.507	1.507	1.5067	0.0006	1.1843	0.0006	1.0883	112.1 cm
9 MeV	2.0	100	0	1.442	1.443	1.445	1.4433	0.0015	1.0000	0.0015	1.0000	
		102	2	1.388	1.391	1.389	1.3893	0.0015	1.0389	0.0016	1.0192	
		104	4	1.340	1.344	1.340	1.3413	0.0023	1.0760	0.0022	1.0373	
		106	6	1.293	1.293	1.294	1.2933	0.0006	1.1160	0.0013	1.0564	
		108	8	1.240	1.243	1.242	1.2417	0.0015	1.1624	0.0019	1.0782	
		110	10	1.195	1.194	1.195	1.1947	0.0006	1.2081	0.0014	1.0992	99.2 cm

5.7/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.974	1.979	1.982	1.9783	0.0040	1.0000	0.0029	1.0000	
		102	2	1.921	1.921	1.922	1.9213	0.0006	1.0297	0.0021	1.0147	
		104	4	1.859	1.863	1.864	1.8620	0.0026	1.0625	0.0026	1.0308	
		106	6	1.799	1.799	1.804	1.8007	0.0029	1.0987	0.0029	1.0482	
		108	8	1.743	1.742	1.741	1.7420	0.0010	1.1357	0.0024	1.0657	
		110	10	1.682	1.680	1.682	1.6813	0.0012	1.1766	0.0025	1.0847	115.9 cm
16 MeV	2.0	100	0	1.942	1.941	1.938	1.9403	0.0021	1.0000	0.0015	1.0000	
		102	2	1.881	1.875	1.874	1.8767	0.0038	1.0339	0.0024	1.0168	
		104	4	1.819	1.814	1.822	1.8183	0.0040	1.0671	0.0026	1.0330	
		106	6	1.759	1.764	1.769	1.7640	0.0050	1.1000	0.0033	1.0488	
		108	8	1.706	1.708	1.709	1.7077	0.0015	1.1362	0.0016	1.0659	
		110	10	1.650	1.654	1.655	1.6530	0.0026	1.1738	0.0023	1.0834	118.6 cm
12 MeV	2.0	100	0	1.793	1.795	1.792	1.7933	0.0015	1.0000	0.0012	1.0000	
		102	2	1.731	1.729	1.731	1.7303	0.0012	1.0364	0.0011	1.0180	
		104	4	1.674	1.672	1.675	1.6737	0.0015	1.0715	0.0013	1.0351	
		106	6	1.620	1.620	1.612	1.6173	0.0046	1.1088	0.0033	1.0530	
		108	8	1.558	1.559	1.560	1.5590	0.0010	1.1503	0.0012	1.0725	
		110	10	1.497	1.497	1.497	1.4970	0.0000	1.1980	0.0010	1.0945	105.1 cm
9 MeV	2.0	100	0	1.478	1.479	1.476	1.4777	0.0015	1.0000	0.0015	1.0000	
		102	2	1.421	1.423	1.423	1.4223	0.0012	1.0389	0.0014	1.0193	
		104	4	1.364	1.366	1.365	1.3650	0.0010	1.0825	0.0014	1.0405	
		106	6	1.310	1.313	1.314	1.3123	0.0021	1.1260	0.0021	1.0611	
		108	8	1.253	1.254	1.254	1.2537	0.0006	1.1787	0.0013	1.0857	
		110	10	1.197	1.198	1.197	1.1973	0.0006	1.2341	0.0014	1.1109	88.4 cm

3.8/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	⟨I⟩	StdDev	Io/Ig	StdDev	Sqrt (Io/I)	
20 MeV	2.0	100	0	2.030	2.028	2.028	2.0287	0.0012	1.0000	0.0008	1.0000	
		102	2	1.960	1.958	1.959	1.9590	0.0010	1.0356	0.0008	1.0176	
		104	4	1.887	1.886	1.888	1.8870	0.0010	1.0751	0.0008	1.0369	
		106	6	1.812	1.811	1.813	1.8120	0.0010	1.1196	0.0009	1.0581	
		108	8	1.737	1.737	1.735	1.7363	0.0012	1.1684	0.0010	1.0809	
		110	10	1.664	1.667	1.668	1.6663	0.0021	1.2174	0.0017	1.1034	94.2 cm
16 MeV	2.0	100	0	1.979	1.983	1.983	1.9817	0.0023	1.0000	0.0016	1.0000	
		102	2	1.909	1.905	1.910	1.9080	0.0026	1.0386	0.0019	1.0191	
		104	4	1.820	1.826	1.825	1.8237	0.0032	1.0866	0.0023	1.0424	
		106	6	1.741	1.736	1.739	1.7387	0.0025	1.1398	0.0021	1.0676	
		108	8	1.658	1.660	1.668	1.6620	0.0053	1.1923	0.0040	1.0919	
		110	10	1.585	1.580	1.584	1.5830	0.0026	1.2518	0.0026	1.1189	81.5 cm
12 MeV	2.0	100	0	1.773	1.773	1.772	1.7727	0.0006	1.0000	0.0005	1.0000	
		102	2	1.688	1.690	1.688	1.6887	0.0012	1.0497	0.0008	1.0246	
		104	4	1.609	1.611	1.608	1.6093	0.0015	1.1015	0.0011	1.0495	
		106	6	1.522	1.521	1.526	1.5230	0.0026	1.1639	0.0021	1.0789	
		108	8	1.444	1.442	1.446	1.4440	0.0020	1.2276	0.0017	1.1080	
		110	10	1.360	1.364	1.365	1.3630	0.0026	1.3006	0.0026	1.1404	69.3 cm
9 MeV	2.0	100	0	1.390	1.390	1.390	1.3900	0.0000	1.0000	0.0000	1.0000	
		102	2	1.318	1.318	1.320	1.3187	0.0012	1.0541	0.0009	1.0267	
		104	4	1.242	1.244	1.244	1.2433	0.0012	1.1180	0.0010	1.0573	
		106	6	1.168	1.169	1.169	1.1687	0.0006	1.1894	0.0006	1.0906	
		108	8	1.092	1.092	1.092	1.0920	0.0000	1.2729	0.0000	1.1282	
		110	10	1.017	1.019	1.020	1.0187	0.0015	1.3645	0.0020	1.1681	57.4

3.2/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	<I>	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.986	1.985	1.981	1.9840	0.0026	1.0000	0.0019	1.0000	
		102	2	1.909	1.906	1.904	1.9063	0.0025	1.0407	0.0020	1.0202	
		104	4	1.817	1.816	1.820	1.8177	0.0021	1.0915	0.0019	1.0448	
		106	6	1.741	1.733	1.739	1.7377	0.0042	1.1418	0.0031	1.0685	
		108	8	1.649	1.649	1.650	1.6493	0.0006	1.2029	0.0017	1.0968	
		110	10	1.581	1.578	1.576	1.5783	0.0025	1.2570	0.0026	1.1212	79.4 cm
16 MeV	2.0	100	0	1.905	1.907	1.903	1.9050	0.0020	1.0000	0.0015	1.0000	
		102	2	1.821	1.823	1.816	1.8200	0.0036	1.0467	0.0023	1.0231	
		104	4	1.733	1.734	1.736	1.7343	0.0015	1.0984	0.0015	1.0480	
		106	6	1.647	1.642	1.643	1.6440	0.0026	1.1588	0.0022	1.0765	
		108	8	1.558	1.560	1.557	1.5583	0.0015	1.2225	0.0018	1.1056	
		110	10	1.477	1.473	1.474	1.4747	0.0021	1.2918	0.0023	1.1366	71.0 cm
12 MeV	2.0	100	0	1.683	1.685	1.685	1.6843	0.0012	1.0000	0.0010	1.0000	
		102	2	1.595	1.594	1.595	1.5947	0.0006	1.0562	0.0008	1.0277	
		104	4	1.502	1.501	1.501	1.5013	0.0006	1.1219	0.0009	1.0592	
		106	6	1.406	1.406	1.403	1.4050	0.0017	1.1988	0.0017	1.0949	
		108	8	1.316	1.317	1.316	1.3163	0.0006	1.2796	0.0010	1.1312	
		110	10	1.228	1.226	1.228	1.2273	0.0012	1.3724	0.0016	1.1715	56.2 cm
9 MeV	2.0	100	0	1.266	1.265	1.263	1.2647	0.0015	1.0000	0.0017	1.0000	
		102	2	1.183	1.181	1.181	1.1817	0.0012	1.0702	0.0017	1.0345	
		104	4	1.103	1.103	1.104	1.1033	0.0006	1.1462	0.0015	1.0706	
		106	6	1.020	1.023	1.025	1.0227	0.0025	1.2366	0.0034	1.1120	
		108	8	0.949	0.948	0.948	0.9483	0.0006	1.3336	0.0018	1.1548	
		110	10	0.873	0.873	0.874	0.8733	0.0006	1.4481	0.0020	1.2034	47.3 cm

2.5/0 IORT Applicator

Energy	Depth	SSD	Gap	I1	I2	I3	(I)	StdDev	Io/Ig	StdDev	Sqrt (Io/Ig)	
20 MeV	2.0	100	0	1.921	1.921	1.920	1.9207	0.0006	1.0000	0.0004	1.0000	
		102	2	1.830	1.831	1.829	1.8300	0.0010	1.0495	0.0007	1.0245	
		104	4	1.735	1.738	1.741	1.7380	0.0030	1.1051	0.0019	1.0512	
		106	6	1.619	1.619	1.617	1.6183	0.0012	1.1868	0.0009	1.0894	
		108	8	1.520	1.519	1.522	1.5203	0.0015	1.2633	0.0013	1.1240	
		110	10	1.414	1.419	1.424	1.4190	0.0050	1.3535	0.0048	1.1634	58.7 cm
16 MeV	2.0	100	0	1.847	1.850	1.850	1.8490	0.0017	1.0000	0.0013	1.0000	
		102	2	1.751	1.750	1.752	1.7510	0.0010	1.0560	0.0012	1.0276	
		104	4	1.655	1.654	1.655	1.6547	0.0006	1.1174	0.0011	1.0571	
		106	6	1.554	1.553	1.553	1.5533	0.0006	1.1903	0.0012	1.0910	
		108	8	1.451	1.452	1.450	1.4510	0.0010	1.2743	0.0015	1.1288	
		110	10	1.360	1.360	1.360	1.3600	0.0000	1.3596	0.0013	1.1660	57.9 cm
12 MeV	2.0	100	0	1.500	1.503	1.505	1.5027	0.0025	1.0000	0.0024	1.0000	
		102	2	1.400	1.401	1.403	1.4013	0.0015	1.0723	0.0021	1.0355	
		104	4	1.296	1.299	1.298	1.2977	0.0015	1.1580	0.0024	1.0761	
		106	6	1.199	1.198	1.200	1.1990	0.0010	1.2533	0.0023	1.1195	
		108	8	1.106	1.106	1.108	1.1067	0.0012	1.3578	0.0027	1.1653	
		110	10	1.008	1.008	1.010	1.0087	0.0012	1.4898	0.0030	1.2206	43.6 cm
9 MeV	2.0	100	0	1.000	1.002	1.001	1.0010	0.0010	1.0000	0.0014	1.0000	
		102	2	0.927	0.926	0.927	0.9267	0.0006	1.0802	0.0013	1.0393	
		104	4	0.851	0.852	0.853	0.8520	0.0010	1.1749	0.0018	1.0839	
		106	6	0.773	0.772	0.773	0.7727	0.0006	1.2955	0.0016	1.1382	
		108	8	0.705	0.706	0.706	0.7057	0.0006	1.4185	0.0018	1.1910	
		110	10	0.641	0.642	0.642	0.6417	0.0006	1.5600	0.0021	1.2490	37.9 cm

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The goal of this project was to define and perform the dosimetry measurements required to characterize a set of 18 applicators for use in Intraoperative Radiation Therapy (IORT). IORT is one of the newest tools in the fight against cancer. In IORT, malignant tumors are exposed directly to high-energy electrons delivered through a specially designed applicator mounted on a linear accelerator.

The medical physicist must provide an adequate description of the dose delivery characteristics for every combination of IORT applicator and electron-beam energy. Briefly, the characteristics of interest include: isodose charts, output factors, effective Source-to-Surface-Distances (SSDs), offset factors, and Central-Axis (CAX) profiles.

Each characteristic is important in the IORT treatment planning process. Isodose charts are used to help select the right combination of IORT applicator and electron-beam energy. Output factors and the offset factors are used to scale the prescribed dose to the appropriate number of monitor units (MUs). CAX profiles are used to find surface dose factors, output factors, and x-ray dose factors.

Radiographic film is used to obtain the iosdose charts and CAX profiles. Effective SSDs are measured using a parallel-plate ionization chamber. In general the results are comparable to those found by personnel at Mayo Clinic for their IORT system. The only difference is the observation that effective SSDs are dependent upon the diameter of the IORT applicator and the electron-beam energy. Keywords: Military theses; radiology; Nuclear medicine; (KT)