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DOSIMETRY OF ARC ELECTRON THERAPY

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ABSTRACT

Arc electron therapy is a complex treatment planning and treatment process. The purpose of this paper is to educate sufficiently the medical physicist on its physical and dosimetric aspects so that he would feel comfortable in implementing this technique clinically. The dependence of the dosimetry on beam energy, source-axis distance (SAD), source-collimator distance (SCD), collimator width, patient radius of curvature, patient collimation, and arc angle are described. How to use this information to design the shape of the secondary collimator and the extent of patient collimation is explained. The second half of the paper discusses the clinical aspects of arc therapy. Procedures for treatment planning, construction of collimators and bolus, and treatment verification are discussed. In summary, a cost-benefit analysis is presented, and future areas of development are described.

INTRODUCTION

Electrons are a popular modality for the treatment of tissue near the surface; however, the skin surface may be neither flat nor perpendicular to the incident electron beam. This presents dose uniformity problems due to the multiple scattering of the electrons, particularly if the skin surface is sloping at angles greater than 30°. This frequently occurs in patients, and one case of interest is when the anatomy is approximately cylindrical in shape. One may treat such a surface shape with multiple fixed electron fields, abutting their edges. This leads to areas of increased/decreased dose at the abutted edges. One solution to this problem has been electron arc therapy, which allows one to achieve a more uniform dose near the surface of a cylindrical volume.

The dosimetry and treatment problems of electron arc therapy are in many ways unique to themselves. In particular, one must understand (1) dose measurement techniques, (2) treatment planning techniques, (3) dose calculation methods, (4) mold room techniques, and (5) treatment techniques. This paper will not address dose measurement techniques, but will discuss the others. Each of these topics has been discussed in a recent symposium (Paliwal, 1981), and this paper will concentrate on a summary of concepts presented there followed by more recent advances in the field.

The first half of the paper will describe the physical properties of arc electron beams, discussing collimation, beam dosimetry, and dose algor-

ithms. The second half discusses clinical considerations of treatment planning, construction of treatment aids, and treatment verification. In summary, a cost-benefit analysis is presented, and areas of potential future development are speculated.

PHYSICAL PROPERTIES OF ARC ELECTRON BEAMS

The treatment and dosimetry concepts for arc electron therapy are significantly different from those of rotational photon therapy or fixed beam electron therapy. The dosimetry depends strongly on the irradiation geometry and the multiple scattering of the electrons. This section will discuss: (1) the geometric properties of the electron beam and irradiation technique, (2) the effect of patient and beam geometry on dose distributions, and (3) the application of these dosimetry concepts for treatment.

In arc electron therapy, the treatment aim is to deliver a uniform dose from the surface to some depth (e.g., chest wall-lung interface) with as little dose to tissues or structures outside the treatment volume (e.g., lung) as possible. Ideally, the patient surface would be cylindrical in shape with its axis of symmetry coinciding with the isocenter of the accelerator gantry, and the treatment depth (e.g., patient's chest wall thickness) would be uniform. In practice, these conditions are never encountered, and it is the responsibility of the treatment planner to optimize treatment for individual patient geometry.

Electron beams employed for arc therapy are typically at the same energy as those available for fixed beam therapy. They use the same scattering foils or scanning patterns as the fixed beam for broadening the electron beam. The primary difference in these beams is the complex collimation system required for arc therapy. Electron arc therapy is similar to photon rotational therapy in that the beam rate (MU/minute) and/or gantry speed are varied in order to deliver the proper number of monitor units over the prescribed arc.

A. Collimator Geometry

The electron collimation system shown schematically in Fig. 1 typically consists of three sets of collimators: the primary collimation is provided by the x-ray jaws; the secondary collimator is typically a shaped electron collimator located between the patient and the photon jaws; and the tertiary collimation is typically lead or lead alloy shielding placed on or near the skin surface to reduce the beam penumbra and to spare tissue not at risk. Ideally, the primary and secondary collimation systems should be able to produce a uniform beam up to approximately 25 cm long at 85 cm SSD (for 100 cm SAD) in the dimension parallel to the axis of rotation and as narrow beam as practical in the dimension perpendicular to central axis and within the plane of rotation.

The primary x-ray collimators are typically opened to their maximum extent (35-40 cm at isocenter) in the dimension parallel to the axis of rotation and a smaller extent (10-15 cm at isocenter) in the plane of rotation. This width is based on the fact that the width of the secondary collimator is in the range of 3-7 cm at isocenter. To decrease the width of the primary collimator would result in a decrease in output (Mills et al.,

1982); to increase the width would result in an increase of x-ray dose to the patient, as illustrated in Fig. 2.

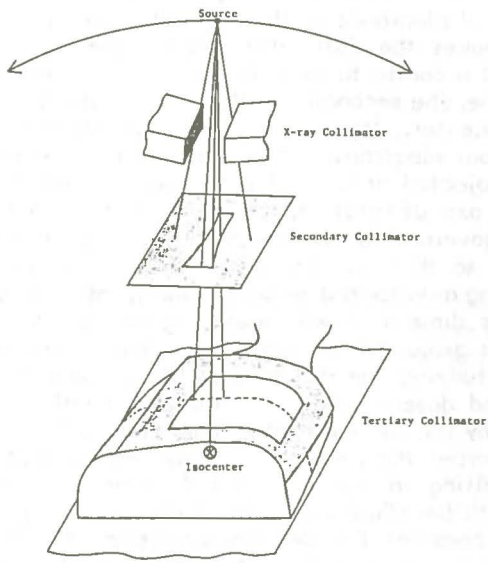


Fig. 1. View of three levels of collimation required for electron arc therapy.

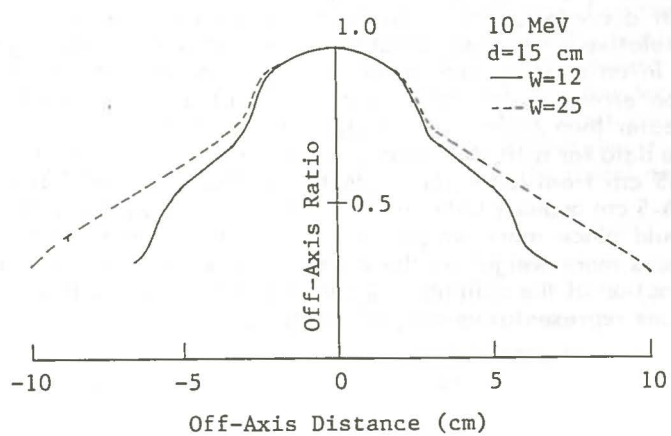


Fig. 2. Comparison of x-ray dose profiles at isocenter at a depth of 15 cm with primary x-ray jaws opened to their normal width (12 cm) and too great of a width (25 cm).

The secondary collimator is the most significant collimator in the system. It should be located as close as possible to the treatment surface. In treatment of the chest wall, the surface is typically 15 cm or more from isocenter. In order to avoid collision with an interfering arm or shoulder of the patient or the treatment couch, the collimator should allow at least another 20 cm of clearance so that it is at least 35 cm from isocenter. In practice, it makes the dosimetry too complex to make this dimension variable so that a comfortable distance is usually selected. For the Varian therapy machine, the secondary collimator is typically located 35 cm from the 100 cm isocenter. Its outside dimension should be sufficient to shield the patient from electrons exiting the primary collimator and scattering outside the projected area of the primary collimator. In the dimension parallel to the axis of rotation, the length of the aperture of the secondary collimator is governed by the length of the target volume. It should be slightly longer so that its penumbra will fall just outside the treatment volume, ensuring a uniform dose within the treatment volume. In the plane of rotation its dimension will vary slightly about a standard width of typically 5 cm projected to isocenter. The rationale for this width is explained by studying the dependence of two key dosimetry parameters, beam width and dose output, on collimator width. The beam profile is characterized by its full width at half maximum (FWHM); the narrower the FWHM, the sharper the penumbral region becomes at the end of the arc rotations, resulting in the need for less patient collimation. As the collimator width becomes small, the beam profile approaches a Gaussian shape with a constant FWHM characteristic of a "strip beam"; as the collimator becomes large, the beam profile becomes uniform in its central region with its FWHM equaling the projected beam width. From the beam shaping perspective, the smallest profile width and hence the smallest collimator width would be most desirable for arc therapy. On the other hand, the dependence of output on the field width has the characteristic shape described by Mills, et al. (1982), which for small field sizes decreases linearly to zero, and for large field sizes approaches a uniform value. As the output decreases, there will be minimal change in the x-ray dose so that the relative x-ray dose would be increasing with decreasing field size, resulting in an unacceptable level of x-ray dose around isocenter. Also, fabrication errors in the collimator construction would result in output errors greater than 2%/mm for widths less than 5 cm.

The data for a 10 MeV beam, 85 cm SSD (ρ=15 cm), and a collimator located 45 cm from isocenter is plotted in Fig. 3. Note that a reference width of 4-5 cm appears to be most practical, based on this data. The 4 cm width would place more weight on the profile shaping ability, the 5 cm width places more weight on the stability of output. These curves are a strong function of the collimator location and energy, and this example was taken as one representative for patient therapy.

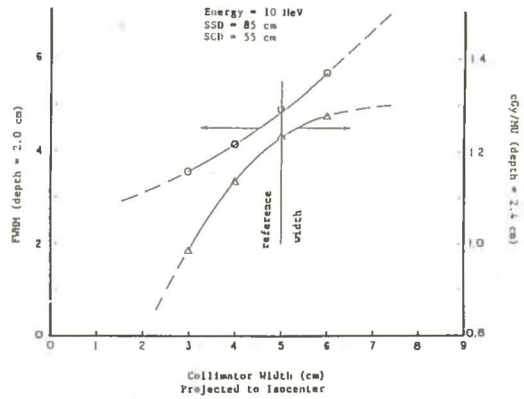


Fig. 3. Beam full width at half maximum (FWHM) and beam output as a function of secondary collimation width. The reference width is the standard width in the central treatment plane and is normally 5 cm.

In arc electron therapy of the chest wall, the radius of curvature of the chest wall near the superior border is normally much less than that near the inferior border. If one simply uses a long narrow rectangular field for treatment, the superior aspect of the chest wall will be overdosed. This has previously been referred to as the velocity effect and was described by Khan, et al. (1977), and has been derived by Ruegsegger and Lyle (1981) and by Leavitt, et al. (1985). This results in an increase in dose as the radius of curvature decreases, an effect qualitatively different from what one might naively expect. Consider the dose at depth, d, in a phantom with radii of curvature $\rho_1 > \rho_2$ so that point P_1 is a distance SAD-ρ_1+d from the source and P_2 is a distance SAD-ρ_2+d (see Fig. 4). As P_2 is further from the source, one might at first think the dose to point P_2 would be less than the dose to point P_1; this certainly would be the case for fixed beam therapy. In arc therapy, where the arc is sufficiently large to establish equilibrium (defined later), the dose is focussed toward isocenter in the arc plane; this results in an increase greater than the decrease due to the beam divergence. To quantify this situation, first consider the plane of rotation (Fig. 5). The electrons are converging toward the isocenter, and the dose distribution is equivalent to the radial dependence of a line source of radiation so that

$$D(\theta, \rho, d, W) \alpha \frac{1}{(\rho-d)} \qquad (1A)$$

In the dimension perpendicular to the plane of rotation, the only effect is the dose decrease due to beam divergence so that

$$D(\theta, \rho, d, W) \alpha \frac{1}{(SAD-\rho+d)} \qquad (1B)$$

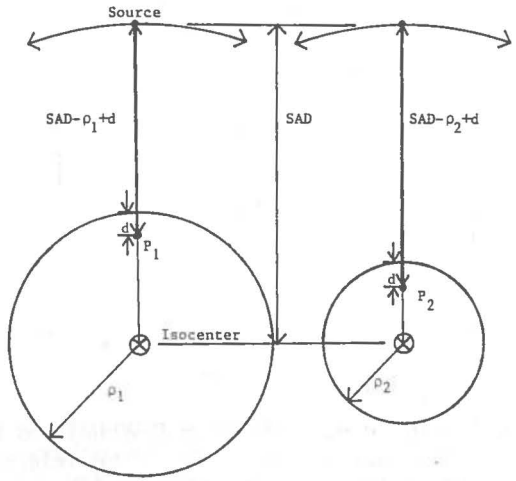


Fig. 4. Geometry of two planes with different radius of curvature in arc electron therapy.

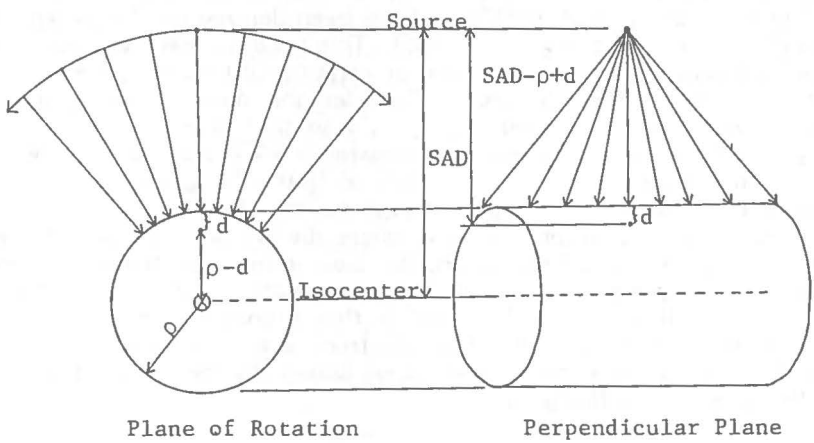


Fig. 5. Conceptual view of field lines for electron fluence in arc electron therapy.

Combining these effects,

$$\frac{D(\theta,\ \rho_1,\ d,\ W)}{D(\theta,\ \rho_2,\ d,\ W)} = \frac{(SAD-\rho_2+d)}{(SAD-\rho_1+d)} \cdot \frac{(\rho_2-d)}{(\rho_1-d)} \qquad (2)$$

which is the result originally defined by Khan, et al. (1977). This dose heterogeneity caused by a variation in radius of curvature along the isocentric axis is removed by shaping the secondary collimator to be approximately trapezoidal in shape with the central plane typically being one's standard (e.g. 5 cm). A method for determining the shape of the secondary collimator has been given by Leavitt, et al. (1985) and is discussed later.

Tertiary or skin collimation is required to restore the penumbra of the dose distribution. The finite-width distribution of the electron fluence for the fixed beam in the plane of rotation results in the creation of a penumbra as conceptually illustrated in Fig. 6. The penumbra within the patient is then restored by the use of skin collimation, which must reach sufficiently outside the original penumbra to shield the scattered electrons and reach inside to near the edge of the target volume. Figure 7 compares the isodose distributions with and without skin collimation. Note that the arc of rotation will be required to extend well outside the arc of treatment, which should be determined for the specific treatment geometry. This added arc segment at each end will vary slightly with energy, being largest for the lowest energy, and with depth of isocenter. It is recommended that the added arc segment determined for the lowest energy be used for all energies; for typical machine geometries the arc of rotation should extend 15° beyond the maximum arc of treatment at both ends.

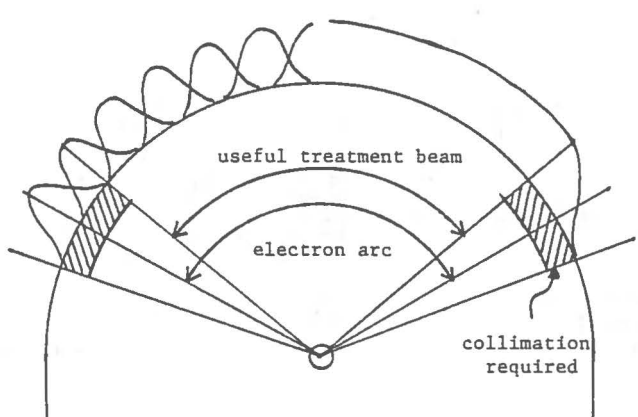


Fig. 6. Schematic demonstrating the azimuthal dose profile for an arc electron beam as generated from the summation of fixed beam profiles. Note the need for collimation at the end of the arc to restore the penumbra.

Another effect observed in the depth-dose curves is an increase in x-ray dose. At isocenter, the x-ray dose expressed as a percentage of the maximum dose will depend on energy, radius of curvature, and angle of arc. It will be approximately proportional to the arc angle, and will decrease with decreasing radius of curvature. For the Clinac 18, x-ray dose for a 15 cm radius of curvature, 180° arc angle ranges from 4% at 6 MeV to 26% at 18 MeV (Leavitt, et al., 1985). With dose of that magnitude outisde the target volume, it is necessary to be aware of its location. Its distribution is similar to that from a rotational x-ray beam, whose diameter is approximately equal to the width of the primary x-ray collimators projected to isocenter, as the majority of the x-ray dose comes from the exit window of the accelerator, the transmission ion chamber, and the scattering foils used for beam flattening. The secondary electron collimator has only minimal effect on attenuating the x-ray dose. Therefore, the width of the primary collimator in the plane of rotation should be set as small as possible, as discussed earlier. Although Leavitt, et al. (1985) originally recommended opening the primary collimator to 30 cm x 30 cm, awareness of this problem led to a setting now of 10 cm x 30 cm on the Clinac 18.

The depth-dose curve for a 90° arc is useful in treatment planning in that it allows one to objectively select a beam energy and to decide whether or not bolus is required to increase surface dose. If bolus is used, the depth-dose curve in the patient must be shifted, frequently resulting in a greater energy beam. Depth-dose data for the full range of radii of curvature and beam energies should be available for treatment planning.

Output

Output is defined as the maximum dose per monitor unit in a cylindrical water phantom on central axis,which is the axis passing through isocenter and bisecting the arc in the central plane of rotation. Output can be used to calculate the monitor units for treatment by

$$MU = \frac{\text{Prescribed Dose at Maximum}}{(D/MU)\ (\theta,\ \rho,\ d_m,\ W)} \qquad (3)$$

where the output, (D/MU), is a function of the radius of curvature of the phantom (ρ), the collimator width (W), the arc angle (θ), and the depth of maximum dose (d_m).

If the radius of curvature is large compared to the collimator width and compared to the electron range, then the output will vary inversely proportionally with θ for angles greater than an equilibrium angle (θ_{eq}). The equilibrium angle is that arc angle, centered on the point of calculation, which if further increased will deliver no significant increase in dose to the point of interest. Figure 10 demonstrates the angular dependence of output for a 15 cm radius phantom at 10 MeV.

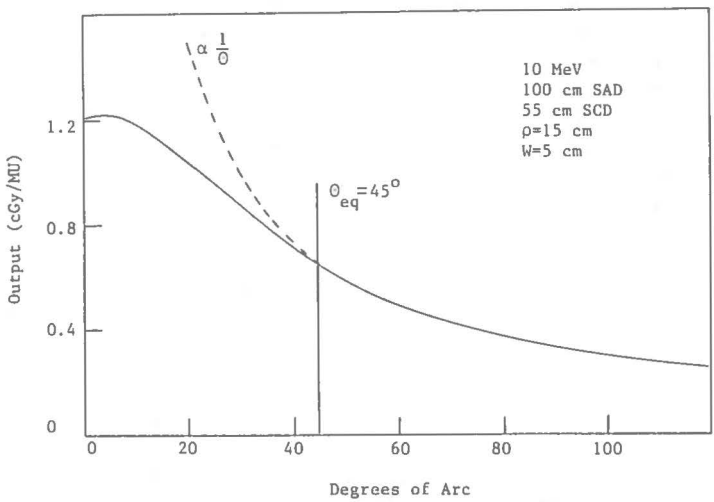


Fig. 10. Output as a function of arc angle. For angles greater than the equilibrium angle, the output varies inversely with arc angle (Kurup, et al., 1985).

If the equilibrium angle is exceeded, then the output should also be directly proportional to the width of the secondary collimator. This occurs because the total number of electrons available for treatment is proportional to the beam width. Figure 11 shows a pencil beam theoretical calculation by Hogstrom and Kurup (1984) of output versus width (actually surface fluence versus width) for a variety of radii of curvature at 7 MeV and an arc angle of 70°. Note that for a 5 cm radius of curvature that the dependence is not linear as the equilibrium criterion is not met. Another way of expressing this data is to plot the output versus radius of curvature as shown in Fig. 12. This data (actually surface fluence versus radius of curvature) should follow the dependence expressed in eq (2), which for the beam parameters of Fig. 12 becomes

$$\frac{D(\theta,\ \rho,\ 0,\ W)}{D(\theta,\ 20,\ 0,\ W)} = \frac{(100-20)}{(100-\rho)} \cdot \left(\frac{20}{\rho}\right) \qquad (4)$$

Data displayed in Figs. 11 and 12 serve as input for the design of the secondary collimator. If the fixed electron beam is uniform in the dimension perpendicular to the plane of rotation, then Leavitt et al.'s formalism for relating doses in different treatment planes reduces to

$$\frac{D(\theta,\ \rho,\ d,\ W)}{D(\theta,\ \rho_0,\ d,\ W_0)} = \frac{D(\theta,\ \rho,\ d,\ W_0)}{D(\theta,\ \rho_0,\ d,\ W_0)} \cdot \frac{D(\theta,\ \rho,\ d,\ W)}{D(\theta,\ \rho,\ d,\ W_0)} \qquad (5)$$

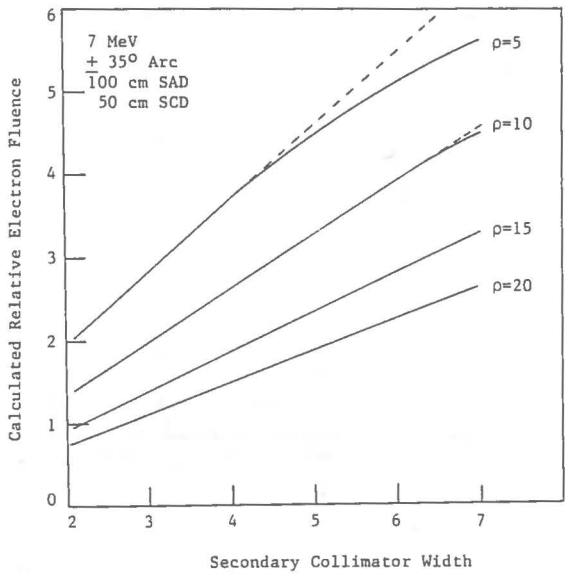


Fig. 11. Output, expressed as electron fluence, varies approximately linearly with collimator width, except when the width begins to equal the radius of curvature (Hogstrom and Kurup, 1984).

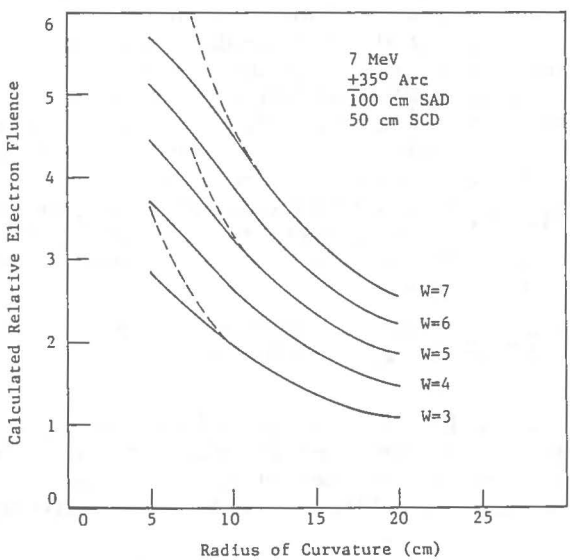


Fig. 12. Output, expressed as electron fluence, varies with radius of curvature approximately according to eq (4), except for small radius of curvature (Hogstrom and Kurup, 1984).

In designing a collimator to produce a uniform arc dose distribution, one would like this ratio to be unity. The first term in the right member of eq (5) can be approximated by eq (2) for an equilibrium arc angle, and the second term is approximated by the ratio of the beam widths. Therefore,

$$\frac{D(\theta,\ \rho,\ d,\ W)}{D(\theta,\ \rho_0,\ d,\ W_0)} = \frac{(SAD-\rho_0+d)}{(SAD-\rho+d)} \cdot \frac{(\rho_0-d)}{(\rho-d)} \cdot \frac{W}{W_0} = 1 \qquad (6A)$$

where W_0 and ρ_0 are the reference width and the radius of curvature in the central treatment plane. Solving for W, the width outside the central plane can be approximated by

$$W = W_0 \frac{(SAD-\rho+d)}{(SAD-\rho_0+d)} \cdot \frac{(\rho-d)}{(\rho_0-d)} \qquad (6B)$$

Similarly, for an equilibrium condition monitor units can be calculated by referencing all dose calculations to a dose calibration at the depth of maximum on central axis for a 5 cm collimator width, a 15 cm radius of curvature, and a 90° arc angle.

The dose per monitor unit is then given by

$$(D/MU)\ (\theta,\ \rho,\ d_m,\ W) \simeq (D/MU)\ (90^\circ,\ 15,\ d_m,\ 5) \cdot \left[\frac{(D/MU)\ (90^\circ,\ \rho,\ d_m,\ W)}{(D/MU)\ (90^\circ,\ 15,\ d_m,\ 5)}\right] \cdot \frac{90}{\theta} \qquad (7)$$

where the term in brackets can be determined from experimental data, computer calculations, or estimated using eq (6A). It should be emphasized that eq (7) is an approximation, which should be reasonably accurate only under the proper equilibrium conditions. It can be used to spot-check the calculation of monitor units using the methodology recommended by one's treatment planning computer or proven clinical system. Equation 7 also holds for any depth, d, under the proper equilibrium conditions, so that it can also be used to calculate changes in the depth-dose curve under different irradiation conditions. As stated earlier, it is not recommended that arc therapy be done without a proper treatment planning dose algorithm, methodology for calculating monitor units, and sufficient dosimetry data to verify their accuracy.

Isodose Curves

Isodose curves are useful (1) to verify the uniformity of the dose in the target volume, (2) to evaluate the dose to normal tissue and structures (e.g. lung), and (3) to make fine changes in the treatment parameters such

as energy, bolus, arc angle, or secondary collimator shape. Isodose curves are characterized by their depth dose and penumbral region. The depth dose and its dependence on the treatment geometry have been discussed above.

The off-axis dose distribution, particularly in the penumbral region, must be understood in both the plane of rotation and in the plane perpendicular to the plane of rotation containing isocenter. In the latter, the field may be long in the cephalocaudal dimension for chest wall treatment so that the off-axis ratio should be considered in the calculation of dose and secondary collimator design. Therefore, it is recommended that a set of off-axis ratios be measured at the depth of maximum with the phantom surface 15 cm above isocenter. This data can then be used to calculate off-axis ratios for other phantom positions, i.e. radii of curvature other than 15 cm, by projecting data along fan lines as recommended by Leavitt, et al. (1985) using the method of Milan and Bentley (1974). The isodose distribution in the plane perpendicular to the plane of rotation for a 7 MeV electron beam with the collimator 45 cm above a 100 cm isocenter has been shown in Fig. 8. This curve not only demonstrates the non-uniformity of the beam as one gets far from central axis, but it also provides valuable information on the penumbra. Note that the 80% isodose line lies approximately 3 cm inside the geometric field edge (approximately defined by the 50% isodose curve at the depth of d_{max}). Therefore, if the maximum cephalocaudal extent of the treatment is 16 cm, then the length of the field must be at least 22 cm in order that the dose inside the skin collimation will be uniform. The dose outside the penumbra is slightly less than 10% at 3 cm outside the geometric beam edge. Therefore, the skin collimation should extent at least 4 cm beyond the light field projected by the secondary collimator in the dimension perpendicular to the plane of rotation. As one goes to a greater energy, the thickness of the skin collimator increases, but the criterion for its extension decreases. Therefore, the rules for the extension of skin collimation determined for the lowest electron energy should be sufficient. Great care should be exercised in assuring adequate skin collimation from stray radiation. Lead strips may be used to supplement any customized patient skin collimator. Their thickness in mm should be equal to the beam energy in MeV times one-half plus a one mm safety margin; for example 10 MeV electrons should be adequately shielded by 6 mm of lead, or commercially available ¼ inch stock.

Fixed field isodose curves measured in the plane of rotation are frequently used to calculate the isodose distribution resulting from an arc. Figure 13 illustrates an unarced isodose distribution for a 10 MeV electron beam; for a cylindrical phantom, the resulting arc dose distribution is seen in Fig. 7, and its penumbra is quite large. The penumbral shape is an end effect, whose width is primarily due to the finite width of the strip beam dose distribution, and whose exact shape is governed by the Gaussian shape of the strip beam profile. We observe that the 50% off-axis ratio varies little with depth and falls at the endpoints of the arc rotation. As before, skin collimation must extend inwards at least about 15°, which corresponds to about 4 cm for a 15 cm radius of curvature. In order to ensure uniform irradiation of the target volume, the arc rotation is 15° beyond the maximum azimuthal extent of the target volume at each end. The skin collimation must also extend about 4 cm or 15° outside the limits of arc rotation to protect from stray radiation. The skin collimation restores the

penumbra as illustrated in Fig. 7. Measurements of this type of dose distribution are also useful in verifying one's treatment planning computer dose algorithms. It is necessary to calculate the uncollimated penumbra accurately for it is required in calculating dose in the patient where energy may be changed during the arc and two arc electron beams are abutted.

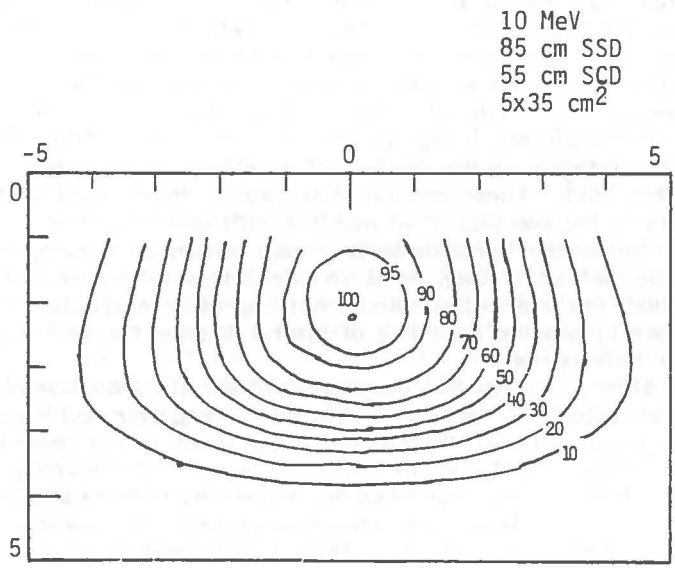


Fig. 13. Fixed beam isodose curve at 85 cm SSD (to correspond with 100 cm SAD, $\rho = 15$) on the Mevatron 77 (Kurup, et al., 1985).

C. Dose Algorithms

For planning patient treatment, a dose algorithm is required. This algorithm is necessary for the design of certain treatment components and for verification that the proper treatment parameters have been selected. The treatment plans must determine a) placement of isocenter, b) limits of arc rotation, c) electron energy, d) bolus, e) shape of secondary collimator, and f) dose output for each arced field. The dose algorithm should be capable of varying a) the location of isocenter, b) limits of arc rotation, c) electron energy, d) incorporation of bolus onto the skin, e) the shape of the secondary collimator, f) the beam weighting, and g) the location of skin collimation for each arced field.

To date, a variety of dose algorithms have been developed for arc electron dose calculations and they fall into two classes, those based on sets of catalogues of measured beam data, and those based on the scattering properties of electrons, i.e. pencil beams. The most standard of the former is the summation of fixed beam dose distributions in small angular steps. This method is typically employed for rotational photon therapy; if the fixed beam dose distribution is calculated from a beam model, it may be attractive to use that model for the fixed beam used for arc electron therapy. If this is done, it is suggested that one measure beam data at the optimal SSD (e.g., if a 15 cm radius of curvature is typical and one has a 100 cm SAD, then measure the beam data at 85 cm

SSD). Also, the proper values for the effective source position should be employed. Finally, one should rigorously confirm the calculated dose with measurement. Leavitt, et al. (1985) describes in detail a methodology for summing fixed beam dose distributions and how to use the algorithm for treament planning.

Another subclass of the algorithm based on measured data is those which integrate angular dose profiles. A method has been described by Khan, et al. (1977) for calculating the dose at the depth of maximum dose by integrating an angular profile. A similar method by Gerber and Purdy (1983) assumes the angle of rotation about the point of calculation is sufficient to completely integrate the angular dose profile. They then represent the integral as the product of an effective angle and the output of the static field. These angular dose profile integration methods are geared more to the calculation of monitor units and dose at selected points rather than to produce bonafide isodose distributions. Laursen, et al. have expanded the method of Khan, et al. to calculate patient dose distributions. These methods use a one-dimensional heterogeneity correction technqiue, and therefore ignore the influence of lateral scatter due to the field edge and internal heterogeneities.

In an attempt to improve the quality of arc electron dose algorithms, a pencil beam algorithm has been developed by Hogstrom and Kurup (1984). It would be possible to use the current fixed beam, pencil beam algorithm (Hogstrom, et al., 1981) and to simulate an arc by summing the dose distributions from several fixed beams. However, with existing computer technology, this would be a time consuming process. Recognizing this, the arc beam has been modeled as a single broad beam along the patient's surface, making computation times comparable to existing fixed pencil-beam algorithms. The algorithm calculates the dose distribution (1) with or without skin collimation, (2) making a heterogeneity correction, (3) for any collimator width, (4) for any constant or changing radius of curvature, and (5) for any arc angle. It requires only a single central-axis depth dose and three off-axis beam profiles. Being based on the physics of electron transport, its preliminary results reported by Kurup and Hogstrom (1985) show good agreement with measurement.

The importance of having an accurate dose algorithm for treatment planning cannot be overly emphasized. To have a successful arc therapy program, the treatment planner must have access to computerized dose distributions and must fully comprehend the strengths and limitations of the dose algorithm used.

CLINICAL CONSIDERATIONS

The clinical decision to treat the post-mastectomy chest wall using electron arc therapy techniques instead of fixed photon or electron fields is based on the following factors:

1) The surface to be treated is curved. The electron arc technique can provide a uniform dose distribution across this curved surface, while a fixed electron field technique suffers from dose nonuniformity due to inverse square law effects and lack of full lateral scatter equilibrium.
2) The surface to be treated may be wider in the dimension of rotation than can be accommodated using a single fixed electron portal. Problems of over- or underdose at the borders between abutted fixed fields are avoided using electron arc techniques.
3) The desired treatment depth changes across the chest wall. The treatment depth throughout most of the field must be adjusted to minimize dose to lung; however, in the mediastinum the treatment depth must be increased to treat deeper lying lymph nodes. Electron arc therapy provides a technique to reduce the lung dose compared to tangential photon field technique, while providing adequate dose to the internal mammary chain. This is most relevant in barrel-chested patients.

Other sites at which one or more of these factors are present include the head, abdomen, and lower extremeties. Because the chest wall is the most common treatment site using electron arc therapy, it will be used to demonstrate clinical considerations common to all electron arc therapy sites.

Before electron arc therapy treatment can begin, the following procedures specific to the individual patient must be completed:

1) definition of the treatment portal
2) measurement of the patient's external contour in multiple planes across the treatment area
3) determination of the location of internal structures lying within the volume of irradiation
4) measurement of the chest wall thickness
5) delineation of the tumor volume as projected in multiple planes across the treatment area
6) determination of isocenter
7) calculation of isodose distributions in multiple planes across the treatment area, with (a) modification in the width of the secondary applicator to provide improved dose uniformity in the cephalocaudal dimension and (b) inclusion of tissue equivalent bolus to compensate for thin sections of the chest wall, which would allow too great a dose to the underlying lung
8) fabrication of the tertiary cast
9) fabrication of the secondary electron arc applicator
10) fabrication of the patient bolus
11) determination of machine settings
12) pretreatment verification (a) that the tertiary cast conforms to the prescribed treatment surface, (b) that the secondary collimator clears the patient and the treatment couch for all angles of the arc, and (c) that the bolus conforms to the patient anatomy

The methodology of how these procedures might be accomplished will be described below. These 12 procedures can involve many members of the radiotherapy team; therefore, clear communication between everyone involved is vital. It is recommended that one person oversee the compilation and correlation of all data necessary to complete these steps. This person will be responsible to communicate essential information between personnel in an effort to provide optimal therapy for the patient.

A. Treatment Planning

Treatment portal and patient contours

Definition of the treatment portal is a clinical decision made by the physician. With the patient lying in the treatment position, the physician marks the borders of the treatment surface. Since individualized tertiary casts are built, the field borders can be irregularly shaped to encompass long scars, extension of disease sites, or the apex of the lung. Positioning devices such as armboards, headrest, and patient immobilizers are used at this point to insure that the patient treatment position can be reproduced.

With the patient maintaining the treatment position, multiple transverse patient contours should be measured. Typically this requires a central plane contour and two to four contours both superior and inferior to the central plane. The registration from contour to contour is vitally important. The simulator couch on which the patient lies during the contour measurement provides a vertical registration for all patient contours. A sagittal (cephalocaudal) laser line provides registration for the left/right orientation of the contours relative to each other. The intersection of this line with each patient contour is marked. The treatment area should be outlined with solder wire or other opaque material and an anterior simulator film taken to document the electron arc field coverage. Typically a supraclavicular photon portal will also be treated. Good field matching can be achieved by placing the central axis of the supraclavicular photon field coincident with the superior border of the electron arc field and using irregular field shaping to define the treatment portal.

Internal Structures and Chest Wall Thickness

CT scans (Fig. 14) are taken at positions corresponding to the patient contours from the previous step and additional planes of interest. Every effort should be made to duplicate the treatment setup positioning during the CT scans, i.e. use a flat table, armboards, headrests, etc., as in the actual treatment. Due to the limited aperture size of CT scanners, some compromises in patient positions may be required. The edges of the field should be outlined with radiopaque markers which are clearly visible in CT scans. Accurate CT description of the patient's internal anatomy is necessary in order to determine the chest wall thickness in each plane and to determine the density of internal structures for treatment planning. The location of the vertebral bodies should also be noted, so that the isocenter location can be chosen to minimize the bremsstrahlung dose to these blood forming structures. An important check should now be performed: How closely do the patient's transverse contours measured manually and by CT agree? To determine this, the CT image can be plotted at lifesize and compared directly with the manually-measured contours. Significant disagreement may be found in the most superior

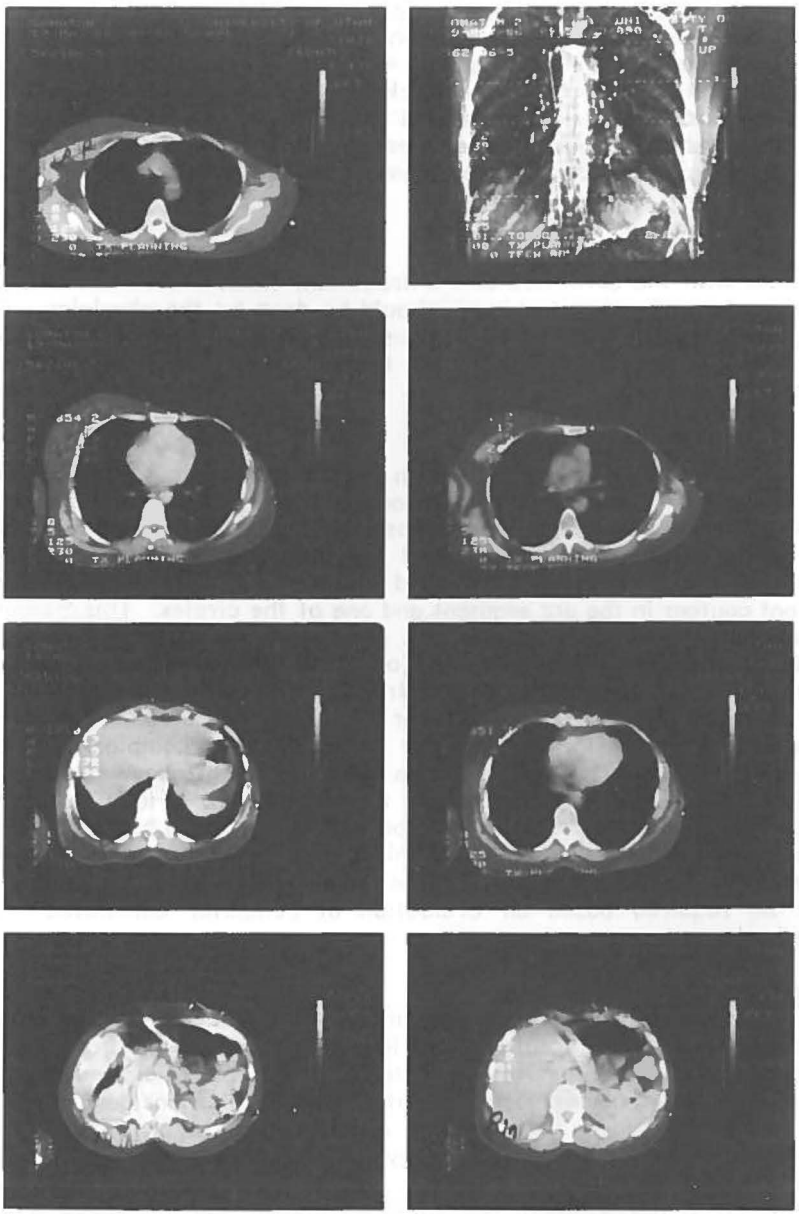


Fig. 14. CT reconstruction of patient anatomy at multiple transverse sections throughout the planned treatment volume. Note correspondence between slices 2-7 with outlines in Fig. 15.

contours if arm position was compromised in order to clear the CT scanner aperture. In these cases, the manually-measured contour should be chosen, and the CT scan should be used to estimate the location and density of internal structures. Chest wall thickness can be measured directly from the lifesize CT plots. As a general rule, the thickness of the chest wall plus any additional bolus is adjusted to allow a dose at the interface between lung and chest wall of no more than 80% of the maximum dose to chest wall.

Tumor Volume

As with the definition of the treatment field, the delineation of the tumor volume, or target volume, should be done by the physician. Often lymphoscintigraphy can serve as a useful adjunct to computerized tomography to determine the depth of lymph nodes to be included in the treatment volume.

Location of Isocenter

The location of isocenter within the patient is chosen to minimize the variation in the radius of curvature across the arc segment to be treated. This can be done manually by circumscribing a set of concentric circles of increasing radius onto a transparent template, then simply adjusting the origin of the template until a good visual match is found between the patient contour in the arc segment and one of the circles. This "isocenter" is marked on the contour and the process is repeated for the patient contours in other planes. This set of "ideal" isocenter points is plotted relative to the patient registration (treatment couch top and sagittal laser line position). An "average" isocenter location, chosen from this cluster of points, is shown in Fig. 15. In order to minimize the complexity of setup, the isocenter is constrained to remain the same height above table top (the patient is treated lying supine on the flat table). However, a slight angulation of the major axis of the patient is allowed (up to five degrees rotation of the treatment couch) if this improves the dose uniformity in the superior and inferior planes. Further modification of isocenter location may be required based on evaluation of computer calculated isodose distributions.

Dose Calculation

Computerized treatment planning is vital to achieving the optimum electron arc therapy treatment. Figure 16 shows collimator and bolus design prior to the computer, and Fig. 17 shows the final treatment plan and isodose distributions. The computer dose distributions generated in all the calculation planes are used to either determine or evaluate 1) the design of bolus, 2) the electron energy for each segment of the arc, 3) the dose rate for each segment of the arc, 4) the shape of the secondary collimator, 5) the optimum isocenter location, 6) the effects of multiple energies used in the arc versus a single energy supplemented with more extensive use of bolus, 7) the dose uniformity across the entire treatment volume, not just a single plane, and 8) the dose to lungs and to blood forming organs through dose-volume histogram analysis.

Through the use of computer planning, alternative plans involving increasing levels of complexity such as different isocenters for different arc segments, bolus which is used during part of the arc and removed during the remainder of the arc, or computer control of the dose rate versus gantry angle can be considered. Only in unusual circumstances are such techniques necessary; computerized treatment planning should be used to design the simplest electron arc therapy treatment techniques that are feasible on a specific patient.

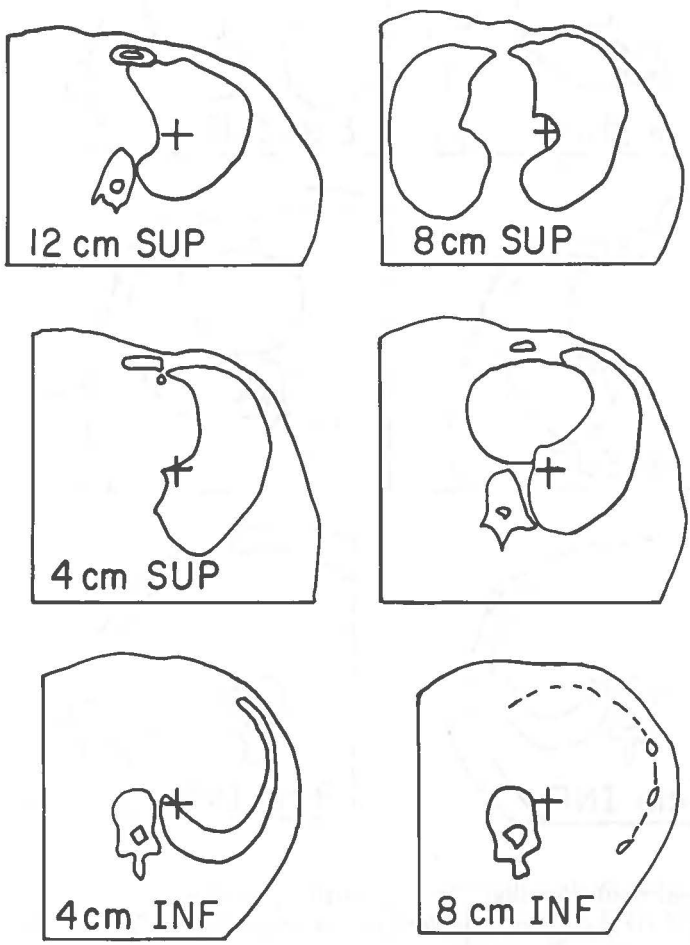


Fig. 15. Treatment Planning: six patient outlines spaced in 4-cm intervals across the chest wall. Isocenter has been chosen to minimize variation of the radius of curvature within each transverse plane.

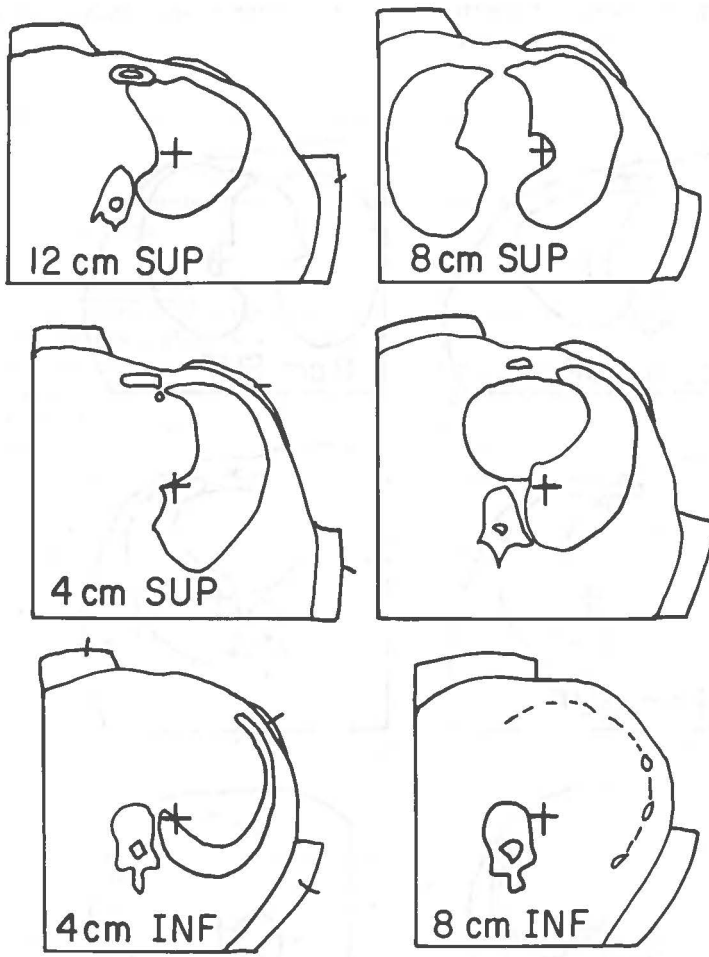


Fig. 16. Treatment Planning: In each outline, tertiary collimation defines the treatment field and bolus is designed to compensate for the thin chest wall.

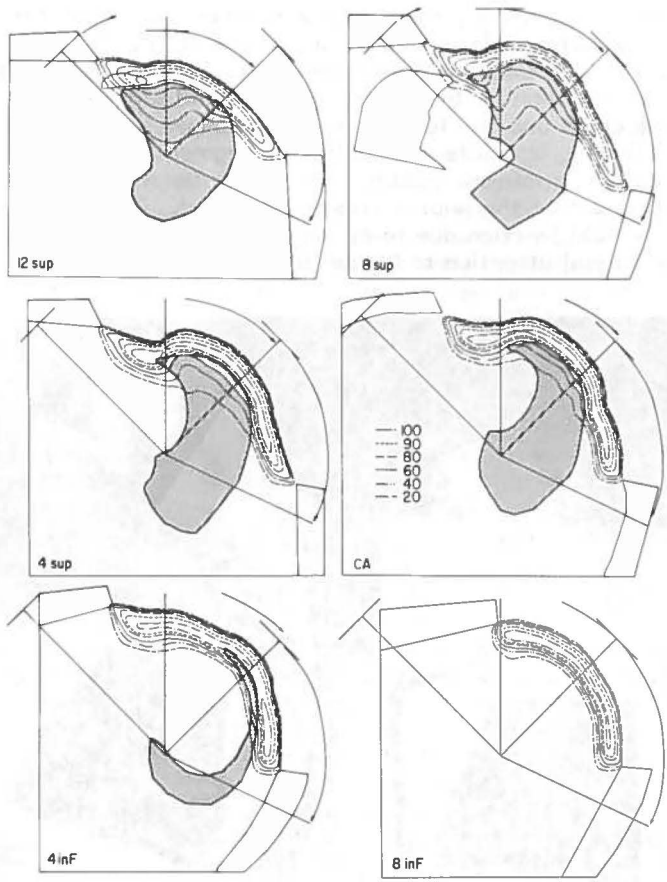


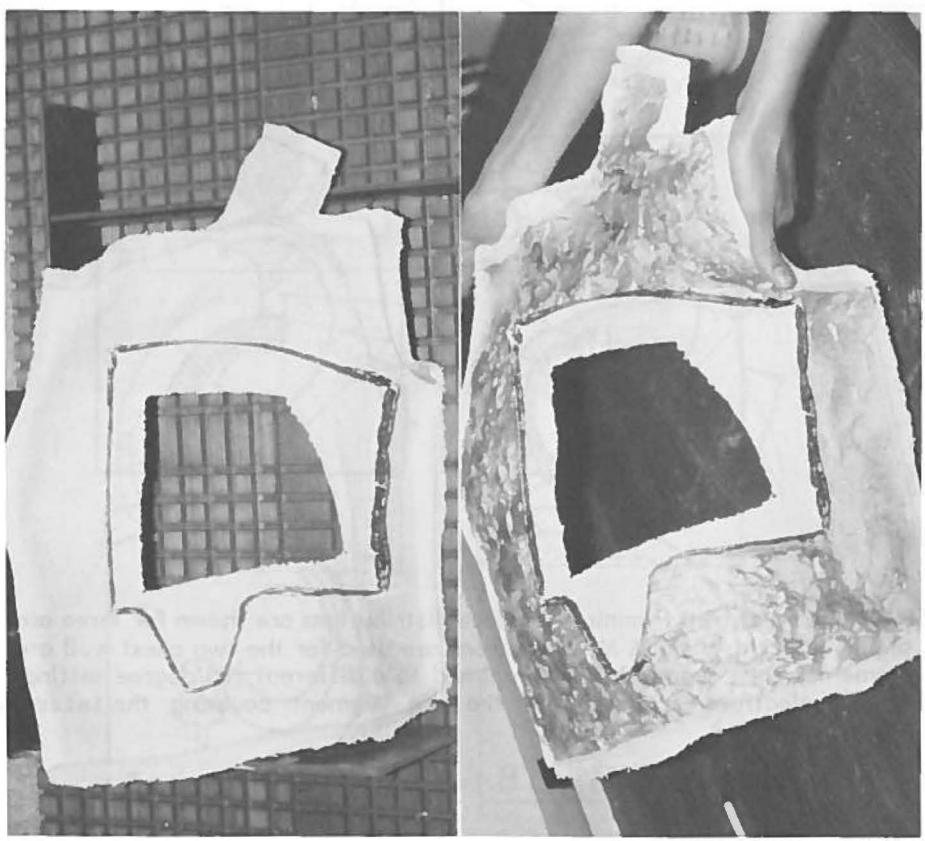
Fig. 17. Treatment Planning: Isodose distributions are shown for three arc segments in this plan. 6 MeV electrons are used for the two chest wall arc segments; each segment is programmed to a different rad/degree setting. 9 MeV electrons are used for the arc segment covering the internal mammary chain.

B. Treatment Aids

Patient Collimation

The design and fabrication of an individualized tertiary collimation cast for each patient is perhaps the most tedious and time consuming task of the entire pre-treatment procedure. Various methods of construction have been reported by Thomadsen (1981); in this report, the technique of Orr (1981) will be described. As soon as the treatment area has been mapped onto the patient cast, construction can commence, and the several steps required for completion can be done in parallel with other pre-treatment tasks. The purpose of the tertiary cast is to sharply define the electron field at the patient's surface. Therefore, the cast is made to fit snugly to the patient's chest. Special care must be taken to insure contact

between the cast and the patient at the superior border of the field. At this border, a photon field is abutted to the electron field. Here the chest contour is usually sloping away from the source (patient thickness is less at the upper border than at the center of the field), so that any separation between the chest and the tertiary cast will allow the divergent electron field to obliquely irradiate an additional segment of tissue beyond the desired electron treatment portal. This same segment of tissue is also irradiated as part of the photon treatment portal. The risk of overtreatment at this field junction due to misalignment of the tertiary cast can be reduced by careful attention to the details of patient setup.



A B

Fig. 18.
A. Plaster shell of the patient chest wall, from which tertiary cast will be molded. Note the irregular shape at the inferior border, designed to include an extended surgical scar.
B. Tertiary cast formed by pouring liquid Cerrobend onto plaster shell. Prior to treatment, excess plaster is removed from the treatment area and foam is added for patient comfort. The plaster shell helps prevent the Cerrobend cast from warping.

A successful technique for fabrication of tertiary casts uses plaster of Paris casting, shown in Fig. 18A, as a platform for the Cerrobend shielding. Figure 18B shows the tertiary shield, which has been constructed using the following steps:

1) With the patient in the treatment position, cover the treatment area with plastic wrap, leaving generous margins on all sides. Secure the plastic wrap to the skin with a thin coating of petroleum jelly.
2) Using a felt pen, trace the treatment area field edges onto the plastic wrap. These lines will transfer to the wet plaster.
3) Begin the plaster process with 6 inch wide bandages. The plaster should extend from inside the treatment area to a peripheral margin outside the area. The margin should be sufficient to shield the patient from electrons outside the treatment field at both the arc boundaries as well as the cephalad and caudal boundaries. Fold the bandage in half so that the 6 inch width is a double thickness. Wet, and cover one border of the area. Alternate edges, keeping the plaster smooth and even. A total of 3 double-thick layers is needed for stability. Shape carefully around the chin and shoulder. Bring the lateral edge down to the table top so that part of the cast weight will be supported by the table. Additionally, an extension can be built superior to the shoulder that can be used to have the table support a portion of the cast. Watch that the extent of the cast on the lateral arm will still clear the gantry during rotation.
4) Allow the plaster to dry thoroughly before removing from the patient. Premature removal will cause warping and the cast will not fit the patient properly. Drying requires approximately 15 to 20 minutes and depends on type of plaster. This time can be shortened by applying heat from a hair dryer to the cast. Although the cast may appear solid after removal from the patient, we recommend letting it cure for 24 hours before proceeding with fabrication.
5) If a missing tissue compensator (wax bolus) will be needed, a separate plaster contour of the treatment area should be made. Redraw the felt marker lines on the plastic wrap; add pen lines corresponding to the central plane and to the levels of CT contours. Cover this area with two double thicknesses of 6 inch wide bandage. When dry, remove and store.
6) After 24 hours, the cast is ready for additional processing. Transfer the treatment area outline from the underside of the cast to the topside. Use the 2 inch wide bandage to build an inner wall on the boundary of the treatment outline and an outer wall at the outside edge of the plaster cast. Liquid Cerrobend will later be contained between these walls. Fold the 2 inch bandage in half lengthwise, so it is now one inch wide. Wet, and apply to the cast, following the treatment border and folding the bandage to a right angle so that part is touching the cast and part is perpendicular to the cast to define the Cerrobend block edge. It is easier to work with several short pieces, particularly around corners. Again, allow drying time for plaster before attempting to pour Cerrobend.
7) Before pouring Cerrobend, smear petroleum jelly to the inner surface of the plaster walls defining the treatment aperture, as later this plaster wall will be separated from the Cerrobend.

8) When working with Cerrobend, protective clothing and gloves should be worn. Liquid Cerrobend is poured on to the cast in small increments so that it will quickly solidify. The aim of this procedure is to slowly build up the alloy to its desired thickness across the entire cast. Pour onto a small area of the cast. Adjust the position of the cast so the surface is flat in a small area, and then pour Cerrobend onto it. Keep cold water bags handy to intercept any rivers of Cerrobend that escape. Repeat several thin applications with cooling time allowed between applications. Continue adding layers until the desired thickness (about 1 cm) is reached.

9) After the Cerrobend cast has been formed, cut away the inner plaster wall and excess plaster covering the treatment area. A soldering iron can be used to smooth the Cerrobend edges if necessary.

10) Line the patient surface of the cast with 1/8" foam for comfort. Spray adhesive works well for attaching the foam to the cast.

11) Shape dental wax to cover the medial and superior edges of the cast. It is believed that the dental wax absorbs low energy electron scatter from the edge of the cast and minimizes adverse skin reactions.

Bolus Fabrication

Frequently a bolus must be fabricated to compensate for a thin section of chest wall and to limit the dose to the underlying lung. The thickness of added bolus needed is determined based on the life size displays of the CT images. This thickness information can be transferred directly onto the plaster cast made in step 5) above. At each CT plane level that includes bolus, find the corresponding level on the plaster contour. Outline the area covered by the bolus on the plaster cast. Cut away the portion of the plaster cast not to be covered with bolus, leaving only the bolus shape, clearly marked with CT cut levels and orientation (superior, inferior, medial and lateral) marks. Build up several layers of beeswax across the bolus to the desired thickness at each location. Smooth the bolus or adjust the wax thickness using a hot blade. When the bolus is near completion, the wax should be removed from the plaster. The bolus thickness can then be verified directly using calipers. The wax should be clearly labeled and oriented for use on the patient. The plaster backing on which the bolus was formed can be used to support the bolus during storage, but is not used during treatment. The exact location of the bolus should be marked on the patient's skin. If necessary, verification that the bolus has been properly built and is properly oriented can be achieved by repeat CT scans through transverse planes intersecting the bolus. A typical bolus is shown in Fig. 19. Note the absence of any sharp edges which could cause dose peturbations in the chest wall.

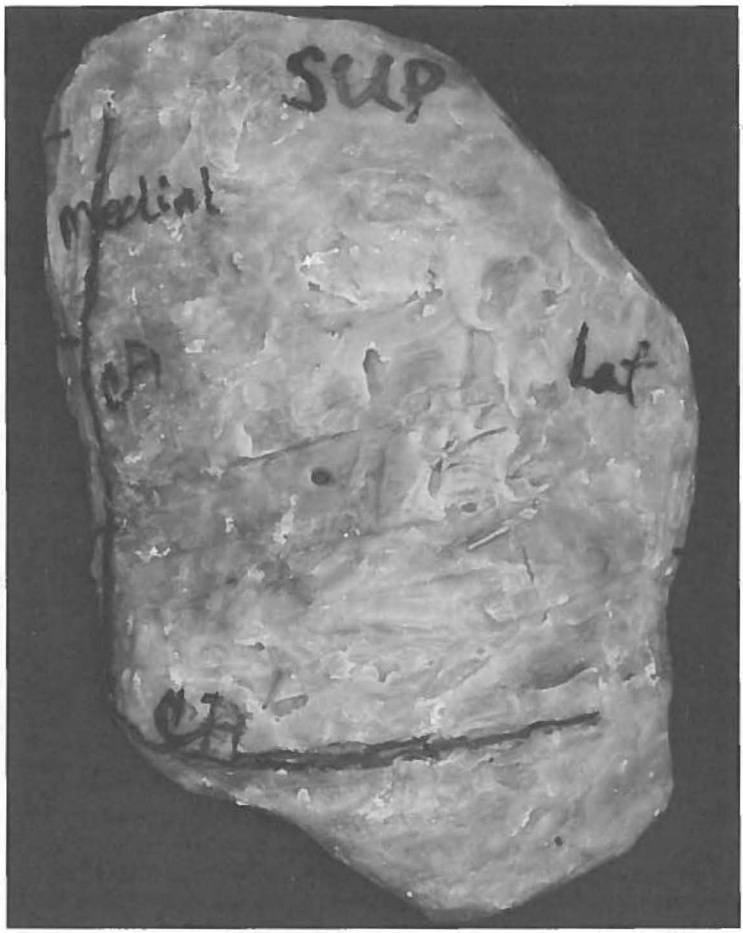


Fig. 19. View of fabricated chest wall bolus. Note the orientation marks.

Secondary Collimator Fabrication

Careful fabrication of the secondary Cerrobend collimator is important, since the shape of this collimator strongly affects the dose uniformity across the treatment surface. The exact width of the secondary collimator at each plane is determined during the treatment planning process using the dosimetry procedures discussed earlier, and will vary in the cephalocaudal direction, depending on the changes in the radius of curvature of patient contour about isocenter from plane to plane. A cutout of the actual collimator shape is made from wood or high density polyurethane foam. The form is taped and sprayed with mold release, and Cerrobend is poured around the cutout to a depth of 1.5 cm. The resulting block, mounted at the appropriate tray position on the machine with the center area removed is shown in Fig. 20. The aperture should be void of all

material; failure to do this will result in mistreatment. Most electron arc setups involve two or more arcs with different weightings or electron energies. A separate block is usually required for each arc segment, since the dose modification needed out of the central plane is often different for each arc segment.

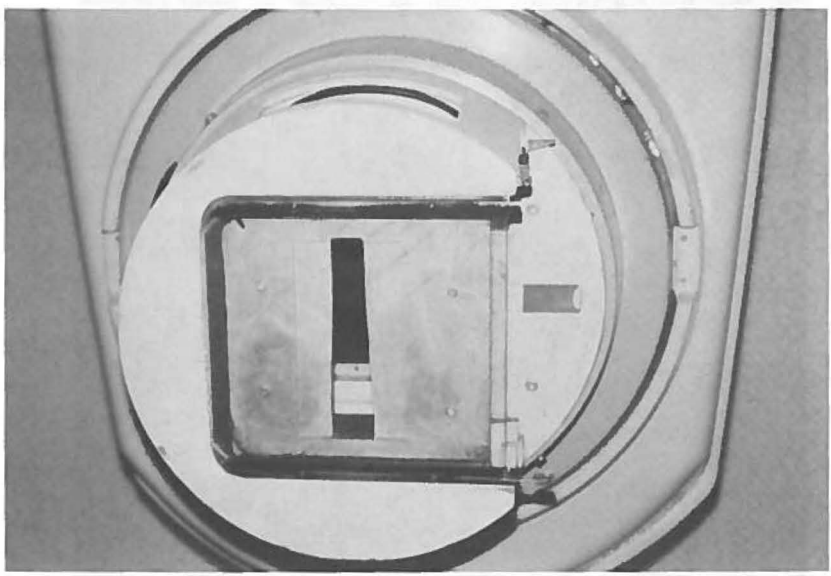


Fig. 20. Secondary electron collimator in Clinac 18 treatment accessory tray. Note changing width of collimator in cephalocaudal dimension.

C. Dose Verification

Treatment dose verification is a necessary precaution in electron arc therapy. One method of dose verification is to construct a phantom of the same shape as the patient and to perform dosimetry measurements under patient irradiation conditions. The plaster of Paris cast from which the tertiary cast is made can be used to form a phantom identical to the patient. It is beneficial to make the outer layer of the phantom removable. TLD's can then be placed both on the surface and at a known depth below the surface. Prior to actual treatment of the patient, this phantom can be used to simulate the treatment. All the parameters to be used in treatment can be set (isocenter, angles of rotation, monitor units, primary, secondary, and tertiary collimation) and an actual treatment dose delivered to the phantom. Readout of the irradiated TLD's then verifies the efficacy of the treatment setup. If unusual deviations from the expected doses are reported, the source of the differences can be sought before patient treatment.

In addition to pre-treatment dose verification, TLD's can be placed on the chest wall of the patient and exposed to a complete treatment.

Readout of these TLD's then gives an estimate of the surface dose to the patient. Similarly, TLD's placed on the patient skin can be covered with a local bolus (care should be taken that the bolus extends far enough laterally to simulate treatment at depth) to the depth of maximum dose buildup in order to verify the patient dose; this will underdose the volume behind the bolus and probably should not be done more than once during a course of therapy. Whatever the technique may be, it is strongly recommended that the electron arc dose be verified for every patient.

CLOSING REMARKS

A. Cost-Benefit Analysis

Electron arc therapy is a very labor-intensive procedure. The startup work required prior to treating patients is roughly equivalent to that necessary to commission the electron modalities on a linear accelerator. Output factors, depth dose, surface dose, beam profiles, and photon contamination must be measured for a series of secondary electron collimators ranging from 3 cm to 7 cm width, for the entire range of electron energies to be used in arc therapy. This information must be reduced to table form for manual calculations and to computer format for computerized treatment planning. Additionally, dose verification through phantom studies should be performed using film, TLD, and ionization chamber dosimetry to verify agreement between calculation and measurement of the absolute dose and relative dose distributions. Additional startup time is required to train the technical staff in electron arc setup procedures, placement of bolus, and secondary and tertiary collimation, and application of supplementary patient shielding.

Once the procedure is adopted and the technical staff are proficient, about 15 hours of dosimetry time is required for each electron arc therapy patient treated. This time is not contiguous, but rather is broken up into segments interspersed with other activities. The following is an approximate breakdown of time requirements:

1) Simulator room procedures (1 hr)
   a. determine patient treatment position
   b. map treatment surface
   c. measure external patient contours
   d. film field borders and simulate supraclavicular field
2) CT scanner procedures (1 hr)
   a. supervise treatment planning CT scans
   b. measure chest wall thickness from CT
   c. determine lung density
   d. compare CT scans with external patient contour
   e. verify bolus design and placement (2nd CT scan)
3) Treatment planning and dose computation (5 hr)
   a. entry of multiple planes into treatment planning computer
   b. optimization of treatment plan
      1. isocenter
      2. arc limits
      3. electron energies
      4. design of secondary collimator shape
      5. design of bolus

4) Mold room procedures (6 hr)
   a. fabrication of secondary collimator
   b. fabrication of tertiary cast
   c. fabrication of bolus
5) Treatment verification (2 hr)
   a. pre-treatment verification of patient setup, including cast and bolus placement
   b. phantom measurements
   c. in-vivo measurements

In addition to the time required by the dosimetry staff, about three hours of patient time is required. Once under treatment, patient setup times are shorter or no longer than would be required to treat the area with fixed electron fields.

Although the effort required for electron arc therapy is large, in many cases the benefits of the technique make the work worthwhile. The dosimetric advantages of electron arc therapy are that a more uniform dose can be delivered to an extended, curved, irregularly-shaped treatment surface while sparing critical underlying structures and avoiding match line problems; the dose distributions can be customized to match tumor volumes of varying depth; and the reproducibility of patient setup is excellent. Experience to date using this technique suggests that survival rates and recurrence rates are equivalent to standard techniques, and that good skin sparing and cosmetic results are achieved (Peacock, et al., 1984).

B. Future Developments in Electron Arc Therapy

In many respects, progress made in electron arc therapy has been constrained by the limitations of the therapy units and the treatment planning algorithms and computers available to the task. We are aware of several problems that have not yet been adequately resolved. Likewise, we appreciate the impact that techniques currently applied to other aspects of radiotherapy could have on electron arc therapy. Continued improvement in electron dose computation algorithms will allow more accurate prediction of the dose to the lung, accounting for interface effects due to lack of electron equilibrium at the lung-chest wall border and for lateral scatter of electrons from the mediastinum into the lung. New techniques for design and fabrication of bolus and secondary and tertiary collimation will streamline the pre-treatment procedures. Application of new or currently available techniques in dose delivery will lead to further improvements in dose uniformity. The following techniques can be considered for application to future electron arc therapy:

1. "Dynamic therapy" collimation techniques currently used in photon irradiation
2. Reduction in photon contamination through use of dual scattering foil design or scan beam technology
3. Computer control of scan beam intensity function, mapping intensity versus gantry angle and position superior or inferior to the central plane
4. Computer control of electron energy versus gantry angle and position

These improvements in treatment planning, accessory fabrication, and dose delivery techniques may make it possible for electron arc therapy to become a more widely used treatment technique.

REFERENCES

RL Gerber, JA Purdy, and J Wong, "Effective Angle Approximation for Calculating Dose for Electron Beam Arc Therapy," Medical Physics 10:524, 1983 (abstract).

KR Hogstrom, MD Mills, and PR Almond, "Electron Beam Dose Calculations," Physics in Medicine and Biology 26:445-459, 1981.

KR Hogstrom and RG Kurup, "Derivation of a Pencil-Beam Algorithm for Arc Electron Therapy," Medical Physics 11:378, 1984 (abstract).

FM Khan, GD Fullerton, JM-F Lee, VC Moore, and SH Levitt, "Physical Aspects of Electron-Beam Arc Therapy," Radiology 124:497-500 (1977).

RG Kurup, KR Hogstrom, and MF Moyers, "Electron Arc Therapy: Comparison of Pencil Beam Calculations with Measurements," Medical Physics 12:509, 1984 (abstract).

F Laursen, B Thomadsen, and B Paliwal, "Electron Arc Therapy Dose Calculations," priviledged communication (1981).

DD Leavitt, LM Peacock, FA Gibbi, and JR Stewart, "Electron Arc Therapy: Physical Measurement and Treatment Planning Techniques," International Journal of Radiation Oncology Biology Physics 11:987-989, 1985.

J Milan and RE Bentley, "The Storage and Manipulation of Radiation Dose Data in a Small Computer," British Journal of Radiology 47:115-121, 1974.

J Orr, "Mold Room Aids for Electron Arc Therapy and Quality Assurance in the Treatment Planning Process," in Proceedings of the Symposium on Electron Dosimetry and Arc Therapy (AAPM, B. Paliwal, ed), p. 341-343, 1981.

B Paliwal (ed), Proceedings of the Symposium on Electron Dosimetry and Arc Therapy (American Institute of Physics, New York), 371 p., 1981.

LM Peacock, DD Leavitt, FA Gibbs, and JR Stewart, "Electron Arc Therapy: Clinical Experience with Chest Wall Irradiation," International Journal of Radiation Oncology Biology Physics 10:2149-2153, 1984.

DR Ruegsegger, SD Lerude, and D Lyle, "Electron-Beam Arc Therapy Using a High Energy Betatron," Radiology 133:483-489, 1979.

DR Ruegsegger and D Lyle, "Electron Arc Therapy Using a High Energy Betatron," in Proceedings of the Symposium on Electron Dosimetry and Arc Therapy (ed. B. Paliwal), p. 223-248, 1981.