FROM THE DEPARTMENT OF RADIATION PHYSICS, CHURCHILL HOSPITAL, HEADINGTON, OXFORD OX3 7LJ, ENGLAND.

CALCULATION OF DOSE DISTRIBUTIONS FOR IRIDIUM-192 IMPLANTS

A. D. WELSH, A. DIXON-BROWN and J. B. H. STEDEFORD

Iridium-192 wire has been used in interstitial brachytherapy at Oxford for over 15 years, and the system used to calculate the dose distribution around an implant is still based upon the method described by HALL et coll. (1966). In view of this, and because there has been a steady increase in the demand for the cross-line curves used in the manual calculation of dose distribution, it seemed that it would be useful to review the original method to improve it and update it if necessary. Since the use of small computers in departments of radiation therapy is now very common, the review was combined with the production of a computer program to assist with the calculation.

Dose rate calculation

It was decided to retain the form of the original calculation by HALL et coll. because the SI definitions of some of the parameters required remain under consideration, in particular the exposure rate constants for interstitial radioactive sources. The calculated dose rates are presented in Gy h^{-1} in soft tissue.

The original expression for the dose rate, I_P (rad/h in soft tissue), at a point P, due to a radioactive line source of length a cm, filtered by a material of thickness d/2 mm is given by the following expression (see Fig. 1):

$$I_p = \frac{8.05\ p\ f}{h} \int_{\theta_1}^{\theta_2} \exp\left(-\mu d/(2 \cos \theta)\right) d\theta \qquad (1)$$

where:

θ_1 = $\tan^{-1}((c-a/2)/h)$

θ_2 = $\tan^{-1}((c+a/2)/h)$

h = perpendicular distance of point P from the wire (cm).

c = the cross-line, i.e. the distance from the centre of the wire to the foot of the perpendicular from P (cm).

8.05 = exposure rate constant for radium 8.3 R/h/mg at 1 cm multiplied by 0.97, the roentgen to rad conversion factor.

p = measured activity of the wire in mg Ra equiv/cm.

f = correction factor to convert the linear activity of the wire, measured through the screenage to true linear activity.

μ = linear absorption coefficient of the filtering material, i.e. platinum (mm^{-1}).

The most significant change made, after eq. (1) had been reviewed, was the reduction of the factor 8.05 to 7.93; 8.3 was replaced by the currently accepted value of 8.25 for the radium exposure rate constant, and 0.97 was reduced to 0.961, a figure which is based on the new W-value of 33.85 eV per ion pair (ICRU 1979). The more commonly quoted value of 0.957 is based on a W-value of 33.7 eV (ICRU 1974).

The activity of the wire quoted by Amersham International Limited is expressed in mR/h/mm at 1

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m, and if this value is used in the calculation, a conversion factor must also be included. The activities quoted by Amersham International Limited are based upon measurements at 25 cm from the wire and exposure rate constants of 0.575×10^{-14} $C \cdot kg^{-1}h^{-1}Bq^{-1}$ (0.825 $R \cdot h^{-1}Ci^{-1}$) at 1 m for radium and 0.335×10^{-14} $C \cdot kg^{-1}h^{-1}Bq^{-1}$ (0.48 $R \cdot h^{-1}Ci^{-1}$) at 1 m for iridium.

The source consists of an active core, 75 per cent platinum and 25 per cent iridium, surrounded by a platinum sheath but, for the purposes of the calculation, it is considered to be a line source filtered by material of thickness equal to the source radius, and since both source materials have similar atomic numbers and densities, the filter was assumed to be 100 per cent platinum. The filtering process may be considered as follows: The photons are attenuated by photoelectric absorption and Compton scattering. The Compton scattered photons remain in the system but have a changed energy distribution. These scattered photons will also be attenuated by the filter with the attenuation coefficients appropriate to their energy. Thus the total transmission through the filter is the number of unattenuated photons plus the Compton scattered photons minus the Compton scattered photons absorbed in the filter. A calculation based on this method using data by STORM & ISRAEL (1970) and summing the coefficients for each energy in the iridium spectrum weighted by the appropriate relative intensity, shows that the coefficient lies very approximately halfway between the attenuation and absorption coefficients (absorption coefficient = 3.66 cm^{-1}, attenuation coefficient = 5.49 cm^{-1}). Since the currently used value of 4.3 cm^{-1} satisfies this requirement it has been left unchanged, although the original source of this coefficient is unknown. The use of such an effective attenuation coefficient is consistent with the findings of DIFFEY & KLEVENHAGEN (1975) when measuring caesium dose rates in water. Errors in the value of this coefficient are not important because the source diameter is very small, and very large variations in the absorption coefficient produce only minor changes to the dose rates.

Eq. (1) makes no allowance for tissue absorption or scattering which will be considered later.

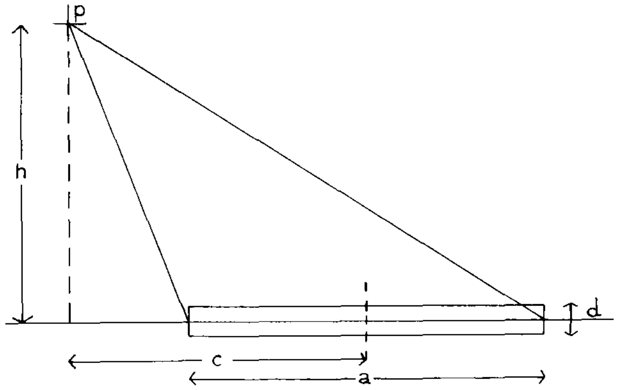

Fig. 1. ^{192}Ir source. Its dimensions and positions relative to the point of calculation p.

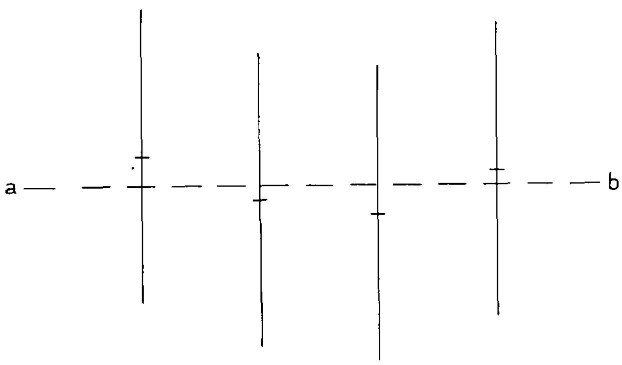

Fig. 2. Straight wire implant. Position of the calculation plane ab, relative to the centres of the wires.

Computer program

The computer program was based, as closely as possible, on the manual system already employed, to facilitate its verification. The processes involved in the computer calculation may be divided into three distinct sections.

(1) The extraction of wire co-ordinates and lengths from the films of the patient.

(2) Calculation of the doses at the points required by the therapist, or at a sufficient number of points to display isodose contours.

(3) Display of the calculated dose distribution.

Data entry. To perform the computation, a complete three-dimensional representation of the wires is required. The information may be available in several forms, the most usual in this department being a pair of orthogonal films or a set of tomograms, although sometimes direct measurements of the wire arrangement are available for moulds or very simple implants. The program has facilities for dealing with any of these methods of data provision, but is unable to deal with shift films which are used in some departments.

Wires entered from a single tomogram are assumed to be straight and parallel to each other,

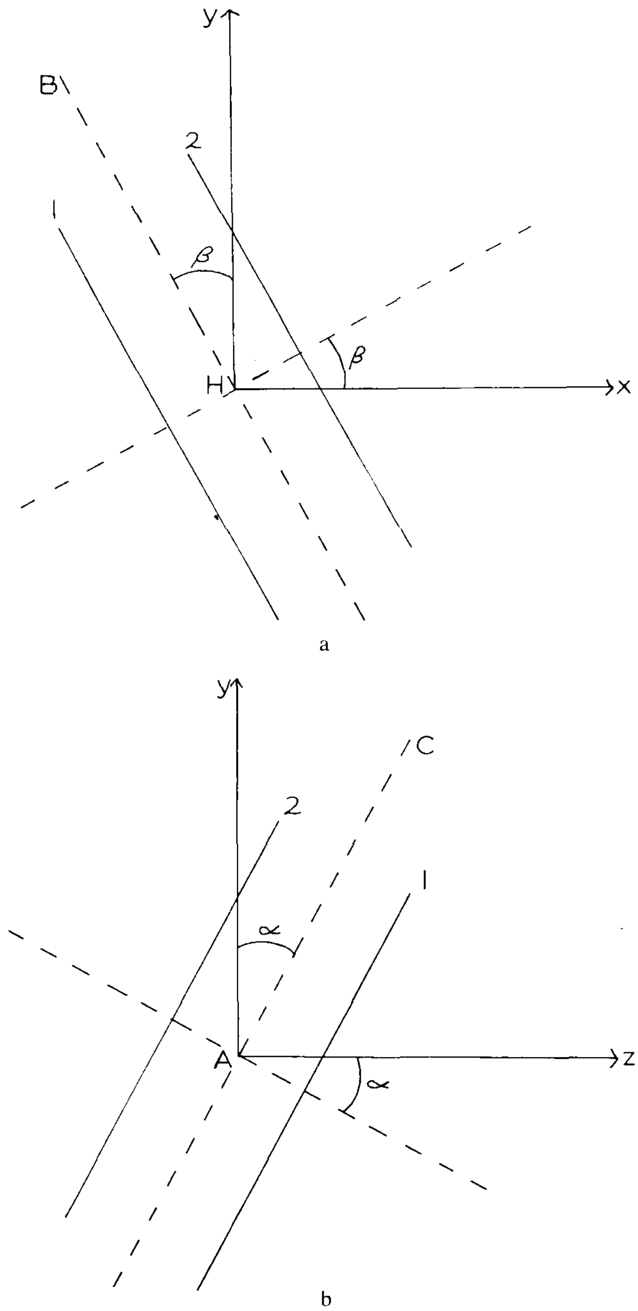

Fig. 3. The average angles that the iridium wires 1 and 2 make with the y-axis on a) view 1 and b) view 2 of a pair of orthogonal films.

since no information to the contrary is available, and it is also assumed that the tomogram bisects each wire unless the relative axial displacements of the wires are entered at the keyboard.

Since the dose rate formula applies to straight wires only, a curved wire must be split into several straight wire elements, and the contribution from each summed to give the dose at a point. Curved

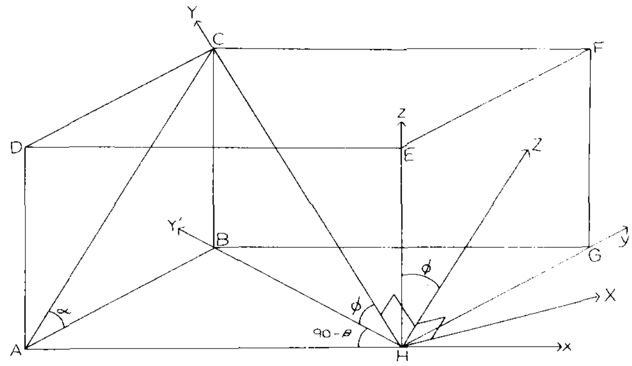

Fig. 4. The relationship of the film co-ordinate system, x, y, z with the calculation co-ordinate system, X, Y, Z. The average wire lies along HC, the Y-axis.

wires usually require a pair of orthogonal films to provide adequate data, unless each wire is contained in a plane, and these planes are parallel to each other and the plane separations are known. In this case a single film, taken parallel to the planes will represent the wires adequately and the plane separations may be entered at the keyboard. The operator enters each wire as a series of points which are used to define the elements. Since the operator will naturally select the least number of points which adequately represent a wire, this technique of element definition reduces the number of elements used to the minimum, whilst approximating well to the curvature of the wire. If an alternative technique of dividing the wires into a number of elements of equal length is adopted, the wire curvature may not be well represented unless the element size is small, resulting in a correspondingly long computation time.

If a single film is used the elements are defined as the lines joining two adjacent points entered by the operator. When 2 orthogonal films have been taken, to avoid the difficulty of identifying exactly the same point on a wire for both films, the wire is split into convenient sections independently on each film. The points on the second film corresponding to the ends of the sections entered from the first film, are found by linear interpolation and vice versa. Thus if a wire is divided into 4 on the first film and 3 on the second, since the ends of the wires are points common to both films, the computer splits the wire into 6 elements for the calculation.

The program will evaluate a dose distribution for up to 20 wires each consisting of up to 20 elements, and this has been found to be sufficient for all implants so far encountered. Having entered the

Table

The dose rates in Gy generated when 1966 and 1981 data are used for 0.3 mm and 0.6 mm wires

Wire length (cm)	Dist. along C/L = 0 (cm)	1981 data with tissue absorption 0.3 mm wire	1966 data no tissue absorption 0.3 mm wire	1981 data no tissue absorption 0.3 mm wire	1981 data with tissue absorption 0.6 mm wire
2.0	0.5	0.3498	0.3498	0.3444	0.3470
	1.0	0.1257	0.1255	0.1236	0.1258
	2.0	0.0373	0.0372	0.0367	0.0375
	4.0	0.0098	0.0099	0.0097	0.0099
	8.0	0.0024	0.0025	0.0025	0.0024
5.0	0.5	0.4241	0.4239	0.4175	0.4134
	1.0	0.1874	0.1870	0.1842	0.1850
	2.0	0.0715	0.0714	0.0703	0.0714
	4.0	0.0223	0.0224	0.0221	0.0224
	8.0	0.0058	0.0061	0.0060	0.0058
10.0	0.5	0.4455	0.4453	0.4386	0.4294
	1.0	0.2122	0.2119	0.2087	0.2068
	2.0	0.0936	0.0935	0.0921	0.0924
	4.0	0.0354	0.0357	0.0352	0.0354
	8.0	0.0106	0.0112	0.0110	0.0106

wire co-ordinates, the next procedure is the selection of the plane in which the dose distribution is to be calculated. The therapist may wish to see the dose distribution in any plane through the implant, but the plane in which the dose is usually prescribed, using either the Paris system (PIERQUIN et coll. 1978, MARINELLO et coll. 1978, DUTREIX et coll. 1979), or the method employed at Oxford, is that which cuts all the wires orthogonally, through their centres or as close as possible to this ideal (Fig. 2). At Oxford, for an average wire separation of between 0.8 and 1.5 cm, the prescription dose is given to a point 0.5 cm opposite a central gap beween two wires (PAINE 1980).

A pair of orthogonal films share one common co-ordinate axis, so one film may be regarded as providing the x and y dimensions, and the other the y and z dimensions, the y-axis being common to both films (Fig. 3). The operator selects the calculation plane by entering 2 points on each film along lines which appear to cut all the wires as orthogonally as possible, allowing the average angle which the wires make with the y-axis on each film to be calculated (angles α and β in Figs 3 and 4). The co-ordinate system is then rotated to coincide with the X, Y, Z system in which the wires lie parallel to the Y axis. The plane in which the dose distribution is required is then the X–Z plane. The first point entered on the first film is the origin of the rotations, and the plane in which the dose distribution is calculated will contain this point. The problem of calculating the required rotations from the angles α and β is very similar to that of calculating treatment machine parameters in the treatment of non-horizontal lesions by external beam irradiation (PERRY 1979), and is discussed further in the appendix.

If a tomogram is the source of wire position data, and has been taken correctly, i.e. at right angles to the wires and bisecting them, the required plane for dose prescription is the tomogram plane.

The dose rate calculation. The dose rates are calculated from eq. (1) with the updated parameters and the wire position data. The Sievert integrals required by eq. (1) are supplied in the form of a table, and the dose rates are calculated on a 2 mm grid, the size of the matrix being specified by the operator. This grid separation is sufficiently small to allow accurate interpolation between the points, unless the points are very close to the wires.

Display of the results. The results may then be displayed either in the form of dose rates at particular points required by the operator, or isodose contours plotted from the dose matrix.

Analysis of errors

Errors in the calculation may arise from 2 causes: (1) faults in the dose rate formula (including errors in the constants used in the calculation) and (2) errors in the wire position data supplied to the program because either the films were not taken correctly or data were entered inaccurately from the films. Errors in the first category are usually insignificant compared with those in the second.

(1) As mentioned before, eq. (1) makes a line source assumption, and the error introduced by this assumption varies with the source diameter. The diameters supplied by Amersham International Limited are 0.3 mm and 0.6 mm, and 0.5 mm diameter wire is supplied in France by the Département des Radioéléments, CEA, Saclay. The line source assumption will cause the dose at a point from a 0.6 mm wire to be underestimated by 0.5 to 1.0 per cent depending upon the distance from the source to the point. The error is negligible for a 0.3 mm diameter wire.

Eq. (1) also ignores tissue absorption and scattering. The factor TAF, which may be used to represent this effect, can be written as a polynomial for a point source (MEISBERGER et coll. 1968), which varies between 1.017 at 1 cm and 0.925 at 10 cm.

$$TAF = 1.0128 + 5.019\times10^{-3}\ r - 1.178\times10^{-3}\ r^2 - 2.008\times10^{-5}\ r^3 \qquad (2)$$

where r is the distance in cm from the source to the point.

The omission of this effect from the model introduces an error of less than 2 per cent in most situations of practical importance, but may be included in the calculation by supplying a table derived from eq. (2). Since the major contribution to the dose at a point is from the element of wire closest to that point, variations in wire length and cross-line cause only small changes in the tissue absorption factor.

Comparison of the 1966 parameters with the currently accepted values shows that the use of old data introduces a 1.5 per cent error, but since the 1966 formula also omits any correction for tissue absorption, at short distances these errors cancel out, and for distances of up to 4 cm the difference between 1966 dose rates for 0.3 mm diameter wire and the revised curves is less than 1 per cent. A summary of these errors appears in the Table.

(2) Repetition of the dose distribution calculation for the same wire arrangement may show differences of as much as 5 per cent in the doses at individual points although the average discrepancy is much less than this (<3%). These differences have been investigated and shown to be due to small variations in the wire position data and the position of the calculation plane. A change of 0.5 mm in wire position may cause a large variation (>5%) in dose rate for a wire separation of the order of 1 cm, although if the average of a few points is considered the variation introduced by such a movement is usually small.

The conclusion to be drawn from this analysis is that if the wire positions are entered carefully and a representative dose rate is chosen for the prescription of the dose, any errors that occur will not exceed 3 per cent.

If required, copies of cross-line dose rate graphs for wires of 0.3 mm, 0.5 mm and 0.6 mm diameter are available from the Churchill Hospital at a nominal charge.

Appendix

Calculation of angles of rotation

Let the co-ordinate system in which the wire position data is initially entered have axes x, y, z and the final co-ordinate system in which the dose distribution is calculated have axes X, Y, Z. For ease of calculation the X, Y, Z co-ordinate system must be such that the wires lie parallel to the Y axis, and the plane in which the dose distribution is calculated is then the X–Z plane.

Referring to Fig. 4, ABCD is a plane representing a lateral film, ABGH represents an a.p. film; the diagonal HC represents the 'average' wire, AC is the projection of the wire onto the lateral film, and HB is the wire projection on the a.p. film. H is at the origin of the system, α is the angle which the wire projection makes with a line parallel to the y axis on the lateral film, and β is the angle which the wire projection makes with the y axis on the a.p. film.

It is necessary to find the angles through which the x, y, z axes must be rotated, so that they coincide with the X, Y, Z axes, and referring to Fig. 4 it may be seen that to achieve this the initial x, y, z co-ordinate system must be rotated through an angle β in the x–y plane, resulting in the co-ordinate system X, Y′, z, and then this intermediate system is rotated through angle $\varnothing$ in the plane HBCE, to coincide with the X, Y, Z system.

$$\varnothing = \tan^{-1}(BC/BH)$$

but

$$BH = AB/\cos\beta \quad \text{and} \quad BC = AB\tan\alpha$$

$$\varnothing = \tan^{-1}\left(\frac{AB\tan\alpha}{AB/\cos\beta}\right) = \tan^{-1}(\tan\alpha\cos\beta)$$

SUMMARY

After reviewing the method of HALL et coll. (1966) for calculating dose rates from ^{192}Ir wire, small changes and improvements were made and a computer program was written to calculate dose distributions. It was found that the wire position data obtained from films and supplied to the program was the largest source of inaccuracy but that with care the maximum error in the calculated dose rates was 3 per cent. If the original cross-line curves are still used for calculations the additional error introduced into the dose rates at distances of up to 4 cm from the wire is less than one per cent.

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