COMPARISON OF CALCULATED AND MEASURED DOSE AS A FUNCTION OF DEPTH IN A BEAM OF FAST PIONS USED FOR RADIATION THERAPY.

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1. INTRODUCTION.

Two methods are used to map the radiation field produced by a beam of fast pions:

a) Measurements with ionization chambers,

b) Calculations of the energy deposition from a known fluence distribution of the incident particles (pions, muons, electrons, etc.).

In the work performed until early 1979, when an uncertainty of 10% in dose was considered to be acceptable, it was possible to neglect a number of effects which were assumed to contribute less than 10% to the uncertainty.

Recently it has been realised that the uncertainty in dose should be reduced to the order of 3%. In consequence, we have examined several factors, neglected so far, which must be taken into account for the comparison of calculated and measured dose distributions at this level of accuracy.

These factors will be discussed here, and the uncertainty in their values will be estimated. First, those affecting ionisation chamber measurements will be considered, then those influencing the dose calculations.

2. FACTORS NEEDED FOR IONIZATION CHAMBER MEASUREMENTS.

The quantity Q determined in an ionisation chamber is the number N of ion pairs created by the radiation in the ion chamber, divided by the mass m of the gas: Q=N/m. It is calculated from the charge collected in the chamber. A first problem encountered is the incomplete collection of charge due to recombination. Assume that a correction factor Cr is needed to calculate N from the measured value Nx: N=Cr*Nx.

Now, Q must be converted into dose Dg (energy per unit mass deposited) in the gas. For this, the average energy W needed to produce an ion pair in the gas must be known: Dg=W*Q.

Next, the dose Dw in the wall of the ionisation chamber must be calculated. The factor r used for this conversion shall be called the dose ratio , Dw=r*Dg. r can be calculated from the stopping powers S of the wall and gas.

Finally, the dose D in tissue must be calculated: D=k*Dw.

We thus have identified four factors needed to convert the number Nx of observed ion pairs into dose D in tissue: Cr, W, r and k. Each of these factors depends on the position of the ion chamber in the radiation field. We assume that the uncertainty in the determination of m and Nx is negligible.

2.1. RECOMBINATION CORRECTION FACTOR Cr.

In general, the ionization is measured experimentally with several different values of the electric field used to collect the ions. Then an extrapolation is made to obtain the number of ion pairs which would be measured with an infinite electric field, and it is assumed that this value represents the initial ionisation produced by the radiation. We shall assume that the uncertainty of this method is established experimentally.

2.2. AVERAGE ENERGY W TO PRODUCE AN ION PAIR.

A review of W has recently been published by the ICRU (1979). The following conclusions are important for the calculation of average W values for pion dosimetry:

a) it cannot be assumed that W is independent of particle energy at high energies,

b) it cannot be assumed that W is the same for different particles,

c) for most particles and gases, the uncertainty of measured values of W is of the order of 5%.

Except for some preliminary data by Dicello (1979), there are no measured W-values for pions. One could assume that W for pions would be in between that for protons and electrons (Table 1).

TABLE 1. W-values (in eV per ionpair) for protons and electrons (ICRU 1979).

	p	e	ratio
N2	36.5	34.8	1.049
Ar	27	26.4	1.023
CO2	34.5	33.	1.045
CH4	30.5	27.3	1.117

We see that while the ratio is equal to 1.0 within the uncertainty of the data (about 5% for the protons, slightly less for the electrons), except for methane, it tends to be greater than 1.0. Since the uncertainty for most of the W-values given by the ICRU amounts to 5%, at least this uncertainty must be assumed for W-values for pions. A more cautious approach would be to choose an uncertainty of 7% (consisting of the uncertainty of W for protons plus one half of the difference from 1.000 of the ratios in Table 1).

In the peak region of the radiation field (the region where stopping pions contribute to the dose), the W-values must be calculated for the spectrum of the charged particles found to produce ionisation in the chamber. This requires a detailed calculation similar to the one for neutrons (Bichsel and Rubach, 1977). We understand that some work on these calculations for pions has been done at U.B.C. Again, an uncertainty of at least 5% must be assumed (the uncertainty will be compounded by the additional uncertainties of the particle spectra). An estimate made by Turner et al. (1975) gave a ratio of about 1.03 for W(peak) to W(plateau).

2.3. DOSE RATIO r.

In the plateau region, the dose ratio can be approximated reasonably closely by the stopping power ratio calculated with the Bragg-Gray relation. For the peak region, it is again necessary to calculate a dose ratio with a model similar to the one used for neutrons (Bichsel and Rubach, 1977). Calculations for pions are being done at U.B.C.

No absolute measurements of stopping power have been made for pions, but relative measurements have been made for some solids (Nordin and Henkelman, 1978). No measurements have been made for gases. Therefore we must use the measurements with other particles and rely on theory to obtain data for pions. In recent reviews (Bichsel, 1977 and 1978) it was shown that the measurements of stopping power S with protons at energies above 1 MeV in gases differed by as much as 10%. Only for alpha particles there are some accurate measurements at energies above a few MeV (Martin and Northcliffe, 1962).

There are no measurements accurate enough to confirm the accuracy of the energy dependence of the Bethe theory to better than about 1%. The measurements by Tschalaer and Bichsel (1967) showed possible differences between theory and experiment of the order of 1%. It appears to us to be advisable to assume an uncertainty of 2% for any stopping power calculated by extrapolation over extended energy ranges in addition to the uncertainty due to the experiments. Altogether, an uncertainty of 3-5% should be assigned to dose ratios calculated with stopping power data. Our guess is that r(peak) will be about (3+2)% smaller than r(plateau).

2.4. DOSE CONVERSION FACTOR k FOR WALL TO TISSUE.

In the plateau region, k will be approximated quite closely by the stopping power ratio of tissue and wall, and its uncertainty will be that of the stopping power plus the uncertainty of the values of the fluences for the several particles used for the calculation. In the peak region, the uncertainty in the Kerma for the pions and of the capture coefficients for pions and muons in the different compounds will be added to the uncertainties in stopping powers. At present, the major uncertainty is probably in the Kerma for carbon and oxygen.

3. FACTORS NEEDED IN DOSE CALCULATIONS.

In the comparisons made between calculated and measured depth dose curves, we considered it important to reproduce the peak of the dose curve if the calculation is normalized in the plateau region. We found that the following effects influenced the height of the peak:

1. divergence of the beam
2. asymmetry in the straggling function
3. the fraction and spatial distribution of decaying pions and muons
4. assumptions about the stardose
5. depth dose curves and spatial distribution of electrons

In addition, problems were caused in some instances by inadequate statistics in the number of incident particles for the calculations. For absolute range measurements, the meniscus of the water surface must be taken into account. The influence of the choice of the multiple scattering model used has not yet been explored (in particular, nuclear scattering has not been considered so far). A discussion of these problems follows.

wrong

range shift / momentum ? ∆p/p

3.1. DIVERGENCE OF BEAM.

If the beam of charged particles is divergent, the fluence in the plateau region will be larger than the fluence in the peak region. If the dose contribution by stars can be considered to be localized (i.e., most of the energy deposition by the star is in a volume smaller than the dosimeter), the ratio of peak to plateau will be proportional to the ratio of fluences. Therefore it is easy to make a correction. Its accuracy will be approximately equal to the accuracy with which the fluence ratio is known. The same considerations apply for convergent beams. The uncertainty will of course be given by the uncertainties in the fluence measurements.

3.2. ASYMMETRY IN THE STRAGGLING FUNCTION.

Lewis (1952) showed that the range straggling function is asymmetric. So far, we have not had enough time to either reproduce his results correctly or to apply them to a beam of 80-MeV pions but calculations of the higher moments of the stopping power (Bichsel, 1972) show that the data given by Lewis are correct within 50%. We have written a FORTRAN program calculating the range straggling from the addition of straggling functions for successive thin layers of absorber. Again, we have not had enough time to check our results.

Our preliminary results indicate that the range straggling function should be 5-10% higher than the Gaussian which has been used so far to approximate straggling.

3.3. FRACTION AND DISTRIBUTION OF DECAYING PIONS AND MUONS.

Pions and muons decay during their transit in the beam channel and in the absorber. The angular distribution of the decay products depends on the energy and the polarization of the decaying particle. The accuracy of the model used to calculate these decays can be assessed from a comparison of measured and calculated depth dose curves beyond the peak. We are working with P. Berardo and M. Paciotti on this problem. At present, we do not even have a reasonable estimate of the effect, much less an estimate of the uncertainty in dose due to this effect.

3.4. ASSUMPTIONS ABOUT THE STARDOSE.

Clearly, for a comparison between calculation and measurement, the calculation must be made for the exact geometry of the experiment. If for example an ion chamber with walls of Shonka plastic, filled with tissue-equivalent gas, is used in a water phantom to measure the dose distribution, the calculation must simulate this setup. In particular, an estimate must be made of the fraction of the stardose penetrating from the water into the ion chamber.

3.5. SPATIAL DISTRIBUTION OF ELECTRONS FROM MUON DECAY.

We are working with P. Berardo on improvements in the angular distribution of decay electrons as well as on using better depth dose curves for the electrons (Berger, 1978).

4. CONCLUSIONS.

Some of the various effects discussed above will increase the ratio of the dose at the peak to the dose at the plateau, some will decrease this ratio. We must distinguish clearly between the systematic nature of the effects and the random nature of their uncertainties. If the effects are neglected, the uncertainty of a dose measurement or calculation should be considered to be equal to at least the algebraic sum of the estimated effects plus the rms sum of the uncertainties. If the effects are taken into account, only the rms uncertainty will determine the uncertainty of the dose. While the sum of the effects may be quite small , the sum of the uncertainties of these effects may be quite large. If, for example, nine effects are added, the average uncertainty of each effect should be only of the order of 1% to produce an overall uncertainty of 3%. Our knowledge about the various effects is far from adequate for this accuracy.

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