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DETERMINATION OF DOSE EQUIVALENT IN THE STRAY RADIATION FIELDS AROUND HIGH ENERGY PROTON ACCELERATORS

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A B S T R A C T

The determination of dose equivalent in stray radiation fields around GeV proton accelerators is made in different ways at the various accelerator laboratories around the world. The basic methods are:

1. Spectral fluence measurements of the components in an equilibrium hadron field and calculation of dose equivalent (H) by means of recommended fluence to dose equivalent conversion factors.

2. Measurement of absorbed dose (D) and determination of the quality factor (Q) in the stray radiation field where the multiplication of both quantities results in a value for H.

3. Separate determination of H for three components, neutrons up to 20 MeV with "Rem meters", gammas and charged particles with ionization chambers, and hadrons above 20 MeV by the activation of ^{11}C from ^{12}C in plastic scintillators.

At CERN the third method is employed routinely. This method has been compared with the second method, involving direct determination of Q around the CERN 28 GeV and IHEP 70 GeV proton synchro-

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trons in typical radiation fields, i.e., predominantly high energy hadrons, fast or intermediate neutrons, and muons. Quality factors in stray fields were determined both by the recombination chamber and the proportional counter technique.

The results of these comparisons will be reported and differences discussed in the light of calibration and interpretation problems, the latter in view of requirements voiced in the ICRP and ICRU recommendations on dose equivalent.

These comparisons enable an estimation to be made of fluence to dose equivalent conversion factors for hadrons above 20 MeV in a stray radiation field. It will be shown that the conversion factor for the ^{11}C activation method employed around high energy proton accelerators generally tends to be too conservative.

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1. INTRODUCTION

The evaluation of the radiation risk in stray radiation fields encountered around high energy proton accelerators is complicated by the presence of hadrons, leptons, and photons, ranging in energy up to a maximum of several GeV. Due to the normally heavy shielding enclosure of an accelerator and primary extracted proton beams, a particle equilibrium condition exists outside the shield which results in a degraded hadron spectrum with primary particles accompanied by lower energy secondaries.

The basic quantity to be determined is the dose equivalent, which is a product of absorbed dose and a quality factor. This factor is given as a function of the LET of the charged particles depositing the energy [1]. The ICRP has also proposed a relation between the fluence of monoenergetic particles in a broad beam and dose equivalent. Methods of dose equivalent estimation based on particle spectroscopy or on absorbed dose with LET modifications are therefore feasible.

2. HADRON SPECTROSCOPY

As hadrons, both neutral and charged, make up at least 80% of the total dose equivalent (except in special cases where muons are the predominant component), one possible method of solving the problem of evaluating the radiation risk in such fields is to determine the hadron spectrum and calculate the dose equivalent using fluence to dose equivalent conversion factors recommended by the ICRP. These factors are given for both neutrons and protons, valid for unidirectional broad beams of monoenergetic particles normally incident on an anthropomorphic phantom[1].

Hadron spectroscopy is not only cumbersome to use in routine radiation survey work but there are difficulties in the interpretation with this technique. Even at energies below 20 MeV, where neutron spectra are usually determined by means of spherical moderators, results become ambiguous as there exist at least two sets of recommended response functions for multisphere techniques[2].

Above 20 MeV activation threshold detectors are employed which require rather high flux densities and which do not distinguish between neutrons and other kinds of hadrons that are present[3]. This may result in errors in the spectral distributions in the high energy range.

As the ICRP recommendations relate to the maximum dose equivalent for monoenergetic hadrons in a body phantom, the use of these fluence to dose equivalent conversion factors, together with spectra determined in stray radiation fields, will effectively sum the maxima of dose equivalent and hence overestimate the radiation risk.

3. FOUR-DETECTOR METHOD

At CERN radiation surveys are performed with a combination of four detectors[5,6]. The measurement system known by the name of Cerberus is made up of three ionization chambers plus the activation of ^{11}C in a plastic scintillator and allows for the separate determination of dose equivalent for the major components in a mixed radiation field. Neutrons are measured with the ionization chamber version of the Andersson and Braun Rem counter, which has a response over a broad energy range following the ICRP-recommended fluence to dose equivalent conversion. A combination of two ionization chambers, one tissue equivalent (TE), the other CO_2-filled and thus insensitive to neutrons, permits the determination of the dose rate from gamma and minimum ionizing charged particles, e.g. muons in the presence of neutrons. The activation of ^{11}C from

^{12}C in plastic scintillators is used for the assessment of the contribution of the nuclear interactions of high energy particles to the dose equivalent.

Although in general four different measurements are necessary to determine the dose equivalent at each position around a GeV accelerator, the actual system is easy to use and gives additional knowledge about the composition of the radiation field.

4. RECOMBINATION CHAMBER

The effect of recombination of ions created in a gas along the particle track is dependent on the LET of the interacting radiation. Thus with a system of two parallel-plate tissue-equivalent chambers, one operated in the recombination mode, the other in the saturation mode, it is possible - provided that polarization voltage and gas pressure are properly adjusted - to determine both the dose equivalent rate and the quality factor in a mixed radiation field[7-9].

5. PROPORTIONAL COUNTER

The pulse height in a proportional counter is a function of the LET and track length of the charged particle causing the ionization. For a tissue-equivalent spherical counter the total charge in the pulse should be directly proportional to the absorbed dose in a corresponding mass of tissue. The LET spectrum can be inferred from the pulse height spectrum and the dose equivalent determined by weighting this spectrum with the appropriate quality factors as defined by the ICRP.

This rather complicated mathematical procedure would bar the use of the tissue-equivalent proportional counter for routine dose-equivalent estimations. A portable prototype instrument has, however, been developed, making use of non-linear amplifiers for automatically determining both dose and dose equivalent[10,11].

6. CALIBRATION OF THE DETECTORS

The instruments were calibrated such that their readings could be converted to dose equivalent. Gamma calibrations were made with a Cs-137 source. The Rem ion chamber was calibrated in terms of neutron dose equivalent rate using a 2 Ci PuBe source and an appropriate conversion factor. The dose rates from both sources were known to better than 5%. In addition the proportional counter was calibrated using its internal alpha source. The recombination chamber was adjusted to give a QF for PuBe neutrons of 8.

7. COMPARISONS IN STRAY RADIATION FIELDS

The last three methods described above were compared in the stray radiation field at seven different points around the 26 GeV CERN PS and three different points around the 70 GeV IHEP proton synchrotron[13)]. Dose equivalent and quality factor were determined at the same position. Stray radiation levels were monitored with a TE ionization chamber near the place of comparison. The radiation intensity varied by less than 5% during a complete measurement; only in two cases were variations up to 10% encountered, for which corrections were made.

The results are given in Table 1, where points 1 to 7 have been arranged in order of decreasing relative contribution of hadrons above 20 MeV. At points 8 to 10 muons are seen as a high contribution to the gamma plus charged particle dose and are given in order of an increasing proportion of muons in the stray field. The errors given in the table represent the degree of reproducibility of the measurement and are not intended to indicate overall accuracy.

The dose equivalent rates as determined by the three different methods show a good agreement, the maximum discrepancy being about 50%. The Cerberus results are generally the highest, which can be expected since the Rem ion chamber overestimates the neutron dose equivalent in a soft neutron spectrum due to the mismatch of its response curve with the ICRP recommendation at intermediate energies and because of the increase in gamma radiation from (n,γ) reactions in the moderator[14].

At points 2 and 3, however, the dose equivalent measured with the proportional counter is the highest despite the fact that the quality factors estimated by all three methods are similar. This could be due to the differences in wall thickness of the TE chamber of the Cerberus (800 mg cm^{-2}), the recombination chamber (> 1500 mg cm^{-2}) and the proportional counter (500 mg cm^{-2}). In a field with an important component of low energy charged hadrons the tissue-equivalent chamber will therefore underestimate the dose relative to the proportional counter[3]. In these radiation fields the maximum dose equivalent should be near the body surface and no buildup in the body is expected[4].

Quality factors for positions 1 to 7 determined by the Cerberus show a tendency to increase with increasing neutron contribution, which is to be expected. There is, however, an exception in position 6, where apparently a rather hard neutron spectrum was encountered in front of a labyrinth with nevertheless only a small contribution of hadrons above 20 MeV.

The radiation situation at the downstream end of the Linac (position 7) is characterized by the predominance of intermediate neutrons. Hence this is a rather special situation around the CERN Laboratory where the assumption of a quality factor of 5 would underestimate the radiation risk when protection surveys are based on an absorbed dose measurement only. In positions 8 to 10 the quality factor is found to be near one and is lowest when the muon contribution is the highest. As would be expected the correspondence in dose equivalent determined from the three different methods is within 10% for these radiation fields.

8. RESULTS IN THE LIGHT OF ICRP AND ICRU RECOMMENDATIONS

The response of all three monitoring systems is adjusted to give as far as possible the required response. None of them give the required quantity of maximum dose equivalent in the body.

The Rem ion chamber effectively sums the maxima of dose equivalents while the proportional counter and recombination chamber measure dose equivalent at the sensitive volume of the chamber. An additional assumption concerning secondary particle equilibrium is implied when taking the results to refer to the maximum in the body.

These inconsistencies would largely be removed if the dose equivalent index recently recommended by ICRU[14)] were taken to be the measure of radiation hazard.

Another approach would be to establish standard depths for critical organs in the body, as has been done recently by the Commission of the European Communities[15)]. Recommendations of the International Electrotechnical Commission propose a spherical detector with a fixed wall thickness of 800 mg cm^{-2} for the penetrating component of photon and beta radiation in the realization of absorbed dose rate meters[16)]. The same approach in mixed radiation field dosimetry would not only guide the development of new dose equivalent instruments but would also avoid calibration problems for already existing devices.

9. FLUENCE TO DOSE EQUIVALENT CONVERSION FACTORS FOR ^{11}C ACTIVATION

The dose equivalent for the high energy hadron component is conveniently evaluated in stray radiation fields around GeV proton accelerators by means of the reaction $^{12}C \rightarrow {}^{11}C$ in a plastic scintillator. The threshold of this activation reaction is about 20 MeV for neutrons, protons, and pions. At different laboratories - as shown in Table 2, lines 1 to 4 - rather conservative fluence to dose equivalent conversion factors are used. These corresponded to a figure, as recommended in ICRP 4, for 20 MeV neutrons in equilibrium with secondaries. According to the latest ICRP publication 21, a figure of 4 cm^{-2} s^{-1} $mrem^{-1}$ h is valid for monoenergetic neutrons of about 400 MeV (line 9 in Table 2).

At CERN a higher value of 10 cm^{-2} s^{-1} $mrem^{-1}$ h was adopted to be a conservative estimate based on an experiment in a 400 MeV neutron beam (line 6 in Table 2) and resulting[17)] in a figure of 16 cm^{-2} s^{-1} $mrem^{-1}$ h. The conversion factor used at CERN was furthermore supported by calculations performed on different neutron spectra reported around GeV proton accelerators[3)], with values ranging between 23 and 15 cm^{-2} s^{-1} $mrem^{-1}$ h.

The independent measurement of quality factors in the present comparison allows for another approach of an estimation for the ^{11}C fluence to dose equivalent conversion. The factor k is calculated in the following way, assuming somewhat greater errors than given in Table 1 :

$$k = \frac{D \cdot Q - H_n - H_\gamma}{\phi}$$

where D is the absorbed dose rate measurement in the field (10% error), Q the mean of the quality factor, as measured with the recombination chamber and the proportional counter, and the corresponding errors (10-33%), H_n the neutron dose rate (20% error), H_γ the gamma and charged particle dose rate (20% error), ϕ the high energy particle flux density (10% error) as determined by the ^{11}C activation.

Values of k in rem cm^2 with the calculated error are presented in the last column of Table 1. The weighted mean is given in line 8 of Table 2 and supports the adopted conversion factor at CERN.

The importance of high energy secondaries for the activation of ^{11}C from ^{12}C has been shown in a calculation where one of the usually used cylindrical carbon plastic scintillators of 1.25 cm ∅ and length, exposed in a pure neutron beam, leads to a value of 5.2 cm^{-2} s^{-1} $mrem^{-1}$ h for the conversion factor when the dose equivalent includes the contribution from lower energy secondaries (line 10 in Table 2)[22]. While this conversion factor applies to the total dose equivalent, a higher value will be necessary when secondaries below the threshold of activation are measured separately.

10. CONCLUSIONS

The comparison of three different methods for the determination of dose equivalent in stray radiation fields around high energy proton accelerators has shown a good consistency in the results of both dose equivalent and the corresponding quality factor. This agreement of the values enables a reappraisal of the practical fluence to dose equivalent conversion factor for the activation of ^{11}C from ^{12}C, where the presently used figure at CERN is supported.

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Table 1

Comparison of dose equivalent determinations using different methods
(Errors given refer to the reproducibility of the measurements)

Position	CERBERUS					Recombination chamber		Proportional counter		^{11}C conversion factor in 10^8 rem cm^2
	H_{total} mrem/h	H_h > 20MeV (relative proportion)	H_n > 17MeV (relative proportion)	H_γ + ch (relative proportion)	Q	H mrem/h	Q	H mrem/h	Q	
1	27.0±1.6	0.57	0.34	0.09	4.2±0.3	29±9	4.2±0.9	-	-	2.74±1.24
2	17.5±0.8	0.46	0.44	0.10	4.6±0.2	15.2±0.4	5.2±0.5	22.2±1.2	4.5±0.2	3.10±1.13
3	38.0±1.5	0.35	0.54	0.11	4.0±0.2	36.5±0.4	5.6±0.5	47.0±1.6	4.5±0.1	4.99±1.76
4	29.4±1.5	0.28	0.60	0.12	6.1±0.4	18±5	3.6±0.4	-	-	2.21±1.27
5	31.7±2.3	0.09	0.85	0.06	6.1±0.5	26.8±1.2	7.5±0.5	25.2±1.5	4.3±0.1	1.78±7.23
6	22.8±1.3	0.06	0.75	0.19	3.4±0.2	17.0±1.2	3.4±0.4	15.3±0.5	2.2±0.1	-
7	45.2±2.9	<0.01	0.95	0.05	8.6±0.6	40.6±3.4	9.7±0.5	34.9±0.7	7.6±0.2	-
8	1.65±0.12	<0.03	0.57	0.41	1.7±0.1	1.65±0.11	2.1±0.1	1.68±0.18	1.7±0.3	-
9	2.99±0.21	0.11	0.34	0.55	1.5±0.1	2.87±0.46	1.5±0.5	3.10±0.21	1.4±0.1	2.82±8.75
10	5.29±0.44	0.08	0.08	0.84	1.0±0.1	-	-	-	-	-

Table 2

^{11}C fluence to dose equivalent conversion factors

Laboratory, experiment or calculation	Ref.	k in 10^8 rem cm^2	k in cm^{-2} s^{-1} $mrem^{-1}$ h
1. Rutherford Laboratory	18	7.72	3.6
2. BNL Brookhaven	19	6.94	4
3. IHEP Serpukhov	20	6.46	4.3
4. JINR Dubna	21	5.05	5.5
5. CERN		2.78	10
6. Experiment in 400 MeV neutron beam	17	1.74	16
7. Calculation for different spectra around accelerators	3	1.23-1.82	23-15
8. Calculation from rad. survey results (weighted mean)		3.01±0.63	9.2±2.0
9. ICRP recommendation for 400 MeV neutrons	1	6.94	4.0
10. Calculation for 400 MeV beam (total dose equival.)	22	5.32	5.2