THE ASSESSMENT OF RADIATION RISKS IN MIXED HIGH-ENERGY RADIATION FIELDS

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The philosophy behind the early routine dosimetry measurements (pre-1965) made around the CERN accelerators, at that time a 660 MeV proton synchro-cyclotron and a 28 GeV proton synchrotron, was to use radiation detectors whose response in some way parallelled the response of the human body to the stray radiation field (Ref. 1,2). Since it was known that neutrons of energies greater than 1 MeV formed a significant component of the stray field it was natural to use proton recoil counters or to count proton recoils in nuclear emulsions to obtain an estimate of the dose equivalent from this component. Since for higher energy hadrons the main component of dose equivalent came from the inelastic nuclear interactions (stars) in the carbon, nitrogen, etc., of tissue, it was natural to directly relate dose equivalent to the number of stars seen in a nuclear emulsion (Ref. 3) or to the ^{11}C activity induced in a plastic scintillator by inelastic interactions (Ref. 4). A measurement of ionization in a CO_2 ionization chamber, or of blackening of an X-ray film, and an assumption of equilibrium in the radiation field completed the picture with respect to the contributions from direct ionization and enabled an estimate of dose equivalent from all energy deposition mechanisms to be obtained (Ref. 5).

Measurements of absorbed dose were also made with tissue-equivalent chambers. These had two objectives: firstly the quality factors obtained by dividing the dose equivalent by the absorbed dose should be seen to be correctly placed in the range of 1 to 10, given other known physical parameters of the field (e.g. the dominance of muons behind end-stops of low-energy neutrons outside maze entrances). Secondly a measurement of dose by means of a tissue-equivalent chamber when multiplied with a quality factor of about 3 will always give a value of dose equivalent which is accurate to within a factor of 2. Early dosimetry research at CERN tended to concentrate on other ways of determining values of the quality factors, for example from measurements of differential recombination in ionization chambers in order to improve this accuracy (Ref. 6,7).

For technical reasons of sensitivity, reliability and stability of discriminator levels as well as that of international "acceptability", the proton recoil counters were replaced by Andersson-Braun counters, or their ionization chamber version where the pulse structure of the accelerator field made this imperative, for the measurement of dose equivalent from neutrons of several MeV. This carried with it an inherent shift in philosophy since the instrument is based on a BF_3 counter which records the alpha particles produced by the absorption of thermal neutrons in boron. This in no way parallels the mechanisms of dose deposition in tissue but uses calculations of dose equivalent at or near the surface of a tissue-equivalent phantom as a function of neutron energy to define a required instrument response curve, which is then matched by varying the thickness of the polythene moderator or of boron-loaded plastic around the BF_3 counter. Thus the instrument measures the dose equivalent from incident neutrons no matter what the equilibrium condition of the radiation field. This corresponded to the philosophy then in use at accelerator laboratories other than CERN, where activation detectors, multisphere detectors and other forms of particle spectrometers, more or less crude, were used to define the radiation field in terms of fluence quantities. Calculations of dose equivalent as a function of depth in tissue-equivalent phantoms, similar to those referred to above, were used to determine the actual dose equivalent to be attributed to these spectra (Ref. 8). At higher particle energies, however, the maximum of the depth-dose-equivalent curves for monoenergetic particles is not at or near the surface of the body. This led to severe confusion in the determination of dose equivalent in spectra of particles which was not helped at all by the recommendations of ICRP Publications 4 and 21 (Ref. 9,10) or

by the ICRU explanations of their dose-equivalent index (Ref. 11). It was evident that for most spectra around a high-energy accelerator the maximum of the depth-dose curve in a phantom exposure is to be found at a depth of about 1 $g.cm^{-2}$ (Ref. 12).

It has recently been shown that the dose equivalent to be attributed to ^{11}C activity in a plastic scintillator is close to the value originally accepted at CERN for pure neutron spectra to be found outside accelerator shields (close to the original calibration philosophy, Ref. 13). This may have to be modified slightly if theoretical predictions of a significant pion component of the field at energies between 20 and several 100 MeV prove to be correct. A typical (theoretical) neutron spectrum is shown in Fig. 1 (Ref. 14). Below 1 MeV the spectrum has essentially the 1/E form. Above this energy the peaks from evaporation and the intranuclear cascade can be seen. Also shown are cascade spectra of neutrons, protons and charged pions having energies above 20 MeV, normalized by equating the peak values of the neutron spectrum to the first-mentioned calculations (Ref. 13). Figure 2 shows the dose equivalent at a depth of 1 cm in tissue for monoenergetic neutrons, protons and pions without the contribution from primary ionization for protons and pions (Ref. 13). When the spectra of Fig. 1 are folded with these dose-equivalent curves, then it is found that pions contribute about one half of the dose equivalent from incident particles with energies above 20 MeV.

In routine dosimetry one is always faced with the same problem. The techniques used to determine fluence quantities are robust, of high sensitivity and easy to use in an accelerator environment. The techniques based on measuring the interactions in the human body, e.g. LET or event-size spectrometry, may be satisfactory laboratory techniques but generally do not have the required sensitivity for use in occupational radiation protection levels, nor can they cope satisfactorily with the pulsed nature of most stray fields around high-energy proton accelerators. The principal way of determining dose equivalent at CERN is still based on the techniques mentioned above. The multi-detector set consists of a REM/ION Chamber, an air-filled ionization chamber and a tissue-equivalent chamber used with a measurement of ^{11}C activation in a plastic scintillator. This is called the CERBERUS system (Ref. 15). The validity of this system is supported by absolute measurements of the energy response of the various detectors (Ref. 16). In addition, intercomparisons between the CERBERUS system and other methods of assessing dose equivalent, although restricted to experimental non-routine situations, have shown good correspondence between the results obtained (Ref. 17). Routine measurements of the stray radiation field of the CERN accelerators are based on single detector systems, i.e. a single hydrogen-filled ionization chamber or REM/ION chamber. Since the energy spectrum and composition of the field remain fairly stable in time, it is possible to "calibrate" the single detector using the CERBERUS system in the field to determine an appropriate field-quality factor for each detector.

CONCLUSIONS

The risk estimate for persons exposed to mixed radiation fields at CERN is based on a detailed knowledge of the radiation field and of the detectors used, coupled with the results from Monte Carlo calculations of dose equivalent as a function of depth in tissue-equivalent phantoms. Recommendations of ICRP and ICRU have never been slavishly followed, e.g. the conversion factors at high energies of ICRP Publication 4 or the detailed application of the Index Quantities of ICRU, but the philosophy has always been to obtain values of dose equivalent which will overestimate the risk. The introduction of Effective Dose-equivalent in ICRP Publication 26 has clarified which dose equivalent is appropriate to risk estimation, but so far no account has been taken in routine surveys at CERN of the isotropy factors which implies a safety factor of two in the assessment of dose equivalent from low-energy neutrons (Ref. 18).

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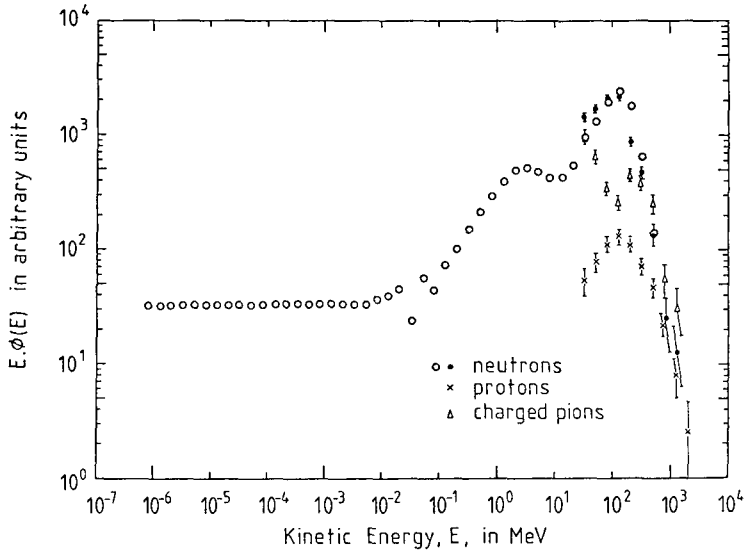

Fig. 1. Theoretical neutron spectrum in the side-shielding of a high-energy proton accelerator (Ref. 14), open circles, compared with high-energy spectra (Ref. 13).

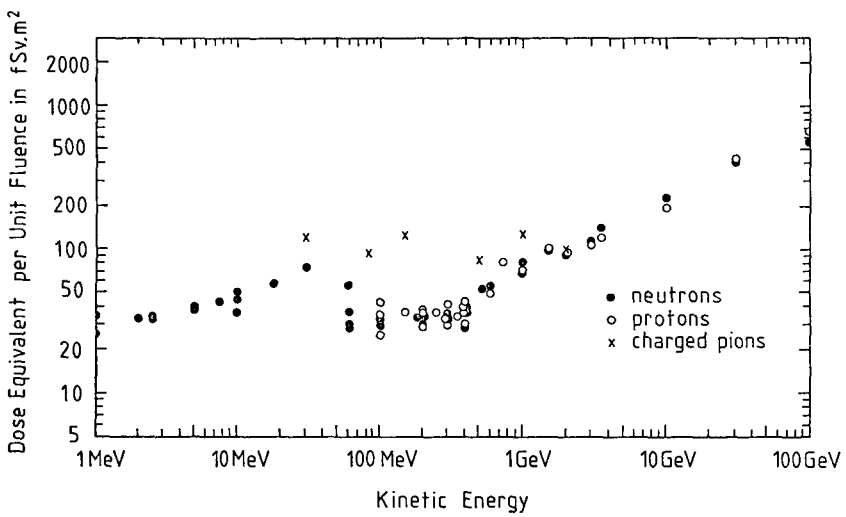

Fig. 2. Dose equivalent at a depth of 1 cm in tissue-equivalent material for monoenergetic neutrons and for protons and pions without the contribution from primary ionization (Ref. 13).