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Implementation of Gy-Eq for Deterministic Effects Limitation in Shield Design

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Space radiation / Deterministic effects / Shielding

The NCRP has recently defined RBE values and a new quantity (Gy-Eq) for use in estimation of deterministic effects in space shielding and operations. The NCRP's RBE for neutrons is left ambiguous and not fully defined. In the present report we will suggest a complete definition of neutron RBE consistent with the NCRP recommendations and evaluate attenuation properties of deterministic effects (Gy-Eq) in comparison with other dosimetric quantities.

INTRODUCTION

The early space program focused on low Earth orbital and lunar missions of a few weeks duration and radiation concerns were for control of deterministic effects in the intense trapped particle environment and during a possible solar particle event[1–4]. With the advent of space shuttle, space stations, and deep space missions with long duration exposures, the concern turns more towards stochastic effects and related career exposures[5]. In these cases, dose equivalent is the limiting quantity considered appropriate for stochastic effects (not with standing high charge and energy, HZE, ions). But, the quality factor of dose equivalent generally overestimates the RBE of deterministic effects. Recently, the National Council for Radiological Protection (NCRP)[6] has recommended that dose rate limitations be made on Gy-Eq rates using field dependent RBE for specific components. We will not address the uncertainty of applying field related RBE measured for cells and small animals to a large mammal such as humans but simply address a consistent method of application of the RBEs as presently defined by the NCRP.

One problem in application of the NCRP defined RBE is the inadequate definition of the neutron RBE across the spectrum of neutrons appearing in the space environment. A full definition of neutron RBE is required for a defined computational procedure for evaluation of Gy-Eq. The RBE as given by the NCRP is shown in Table 1. The RBE values are for the external fields and are adequately defined for the charged particle fields. The neutron RBE below 1 MeV is unclear and above 50 MeV is left ambiguous. The RBE values for the neutron fields are not well defined. We will make a suggestion on the application of Table 1 to space neutron

Table 1. Particle RBE for Deterministic Effects (NCRP 2001).

Particle type	RBE value
Less than 1 MeV neutrons	RBE (fission neutrons)*
1 to 5 MeV neutrons	6.0
5 to 50 MeV neutrons	3.5
Above 25 MeV neutrons	RBE (not more than 1–25 MeV)**
Protons > 2 MeV	1.5
Heavy ions (helium, carbon, neon, argon)	2.5
Heavy ions, all others	2.5

*Evaluated herein as 5
**Assumed herein as 3.5

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exposures although the NCRP recommendations cannot be applied without some ambiguity.

RBE FACTORS

The charged particle RBEs are completely defined when one considers that the range of 2 MeV protons is 0.07 millimeter and will not penetrate to the basal layer of the skin. The neutron RBE is a different matter since neutrons below 1 MeV are assumed to have the same RBE as fission neutrons of unspecified spectrum. Furthermore, neutrons above 25 MeV have RBE no greater than neutrons of 1–25 MeV[6]. We assume the RBE above 25 MeV to be 3.5, the same as that defined by the NCRP[6] on the range of 25 to 50 MeV. This leaves the suggestion for neutrons less than 1 MeV to be resolved.

The first issue for the low energy neutron RBE is the dependence on the fission spectrum assumed. We will use the U^{235} and Cf^{252} fission spectra as examples. The low energy neutron RBE can then be evaluated as follows

$$\mathrm{RBE}_n(<1\,\mathrm{MeV}) = \int_1^\infty \mathrm{RBE}_n(E)C_T(E)\varphi_n(E)dE \Big/ \int_1^\infty C_T\varphi(E)dE$$

where $C_T(E)$ is the specific tissue neutron conversion factor, $\varphi_n(E)$ is the assumed neutron fission spectrum, and the required RBE_n (E) is given in table 1. The conversion coefficients for ocular lens and blood forming organ (BFO) in fig. 1 are taken from ICRP[7] and Yoshizawa et al.[8]. We assume the skin conversion factors to be similar to the ocular lens. We have evaluated RBE_n (<1 MeV) for the most common fission sources (U^{235} and Cf^{252}) and give results in table 2 for skin, lens, and BFO. An RBE value of 5.0 for neutrons below 1 MeV is considered consistent with table 2 and could replace the first entry in table 1 (see footnote).

Table 2. Values for RBE (< 1 MeV) from Current Evaluation.

Tissue/Fission source	U^{235}	Cf^{252}
Skin, Lens	5.14	4.96
BFO	5.01	4.82

RBE IMPLEMENTATION

Field related weighting factors could be readily applied to dosimetric evaluation if the field is sufficiently known. Normally within the space program, the compositional change in local tissue exposure field with penetration depth is evaluated using computational models[9] and dosimetry is augmented with calculations to define the local tissue dosimetric quantities[10]. There is an added complication in application of nonlocal field related quantities to local tissue exposures in a deterministic calculation since the discontinuous nature of the associated field weighting factors (for example, see table 1) requires a discontinuous representation of the field related boundary conditions which rely on numerical interpolation in the computational procedure. In the newly defined RBEs, the charged particle field components are represented by a single value of RBE for all energies and only the neutron field RBE is problematic. In the case of neutrons, we can use the neutron conversion factors to evaluate an average neutron $\mathrm{RBE}_{n,T}$ for each specific

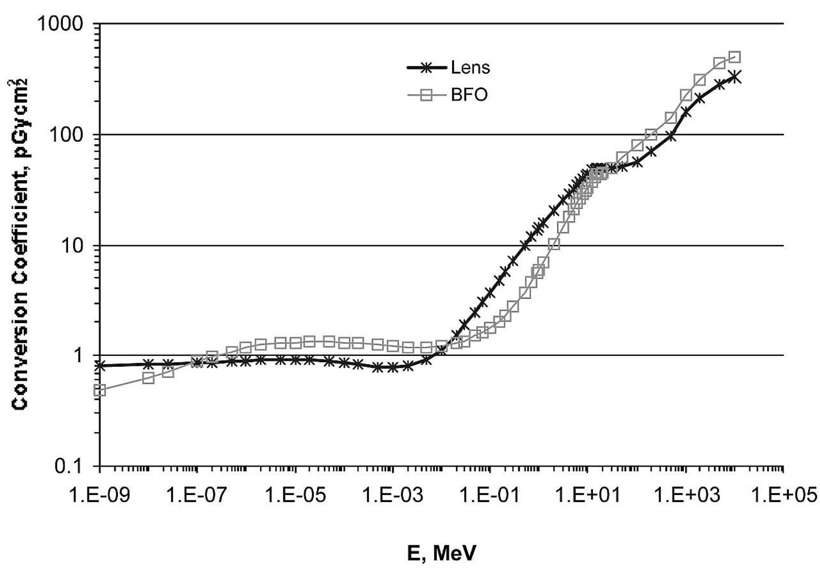

Fig. 1. Neutron dose conversion factors for ocular lens and BFO.

tissue for a given neutron environment as follows:

$$RBE_{n,T} = \int dE\, RBE_n(E)\, C_{n,T}(E)\, \varphi_n(E) \,/ \int dE\, C_{n,T}(E)\, \varphi_n(E)$$

where $\varphi_n(E)$ is the neutron field spectra, $C_{n,T}(E)$ is the specific tissue conversion factor. This value of $RBE_{n,T}$ can be applied to the full neutron environment independent of the neutron energy. In the computation we find little difference in the average $RBE_{n,T}$ for different tissues and take the largest value of the various tissues as the average RBE_n for the field averaged quantity. The computations are implemented by scaling the local particle fields into "effective fields" scaled according to the field RBE. Evaluation of the "effective absorbed dose" resulting from these "effective fields" scaled by RBE is numerically the Gy-Eq for the tissues as required.

As an example, we evaluate the quantity Gy-Eq using the RBE as defined in table 1 and compare to dose and dose equivalent for the solar particle event of September 1989 in figure 2 and for galactic cosmic ray exposure at solar minimum in figure 3 as a function of polycarbonate shielding. The implementation uses the HZETRN[12)] code using the Computerized Anatomical Male (CAM) and Computerized Anatomical Female (CAF)[13,14)] on the website[15)] http://sirest.larc.nasa.gov. It appears that the use of dose equivalent as proxy for Gy-Eq in the past for Solar particle events is not such a large overestimate as previously presumed as seen in figure 2 where dose equivalent and Gy-Eq are nearly equal to large depths. This is not true for the galactic cosmic rays where dose equivalent remains substantially larger at shielding thickness below 20 g/cm^2 and remains high to even great depths as seen in figure 3. What would now be interesting is to see how these results correlate with recent

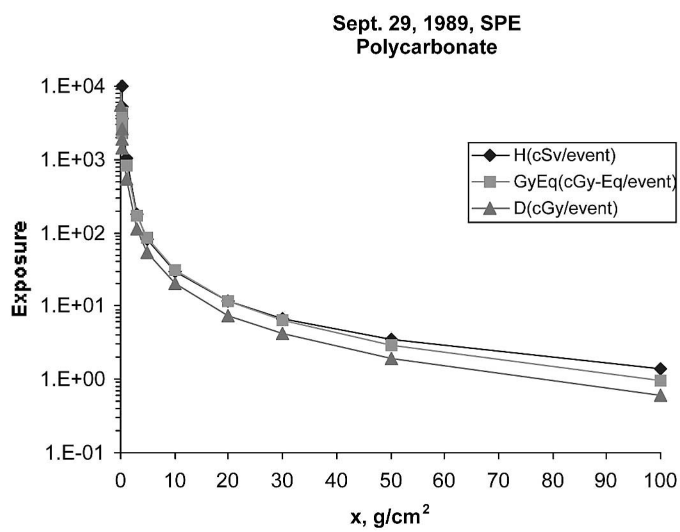

Fig. 2. Attenuation of dosimetric quantities within polycarbonate shield of thickness x.

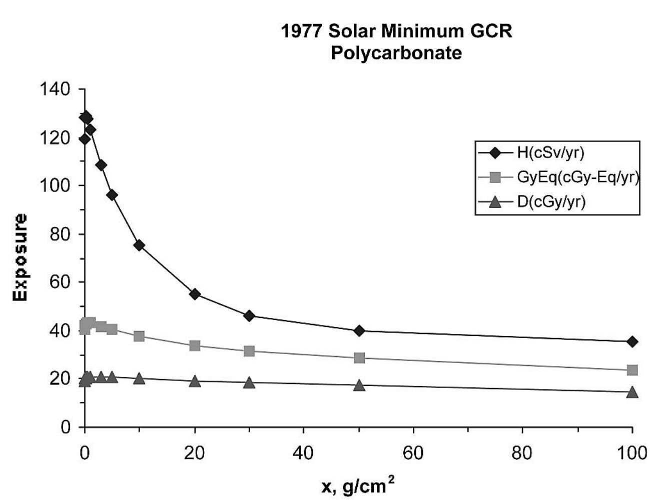

Fig. 3. Attenuation of dosimetric quantities within polycarbonate shield of thichness x.

observations on cataract formation in the astronaut corps where significant differences are seen in cataractogenesis between low and high inclination orbits are observed[11)].

CONCLUSIONS

We proposed a resonable solution to the ambiguities in neutron RBE's defined by the NCRP for deterministic effects and implemented a computational procedure. Past use of dose equivalent as proxy for Gy-Eq in solar particle events seems justified but results in large overestimates in HZE dominated exposures.

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