Life Sciences in Space Research 1 (2014) 96–102

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

Quality factors for space radiation: A new approach

Thomas B. Borak [a,*], Lawrence H. Heilbronn [b], Lawrence W. Townsend [b], Rafe A. McBeth [a], Wouter de Wet [b]

[a] Department of Environmental and Radiological Health Sciences, Colorado State University, Ft. Collins, CO 80523-1618, United States
[b] Department of Nuclear Engineering, University of Tennessee, Knoxville, TN 37996-2300, United States

ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 7 February 2014
Accepted 10 February 2014

Keywords:
Space radiation risk quality factors

ABSTRACT

NASA has derived new models for radiological risk assessment based on epidemiological data and radiation biology including differences in Relative Biological Effectiveness for leukemia and solid tumors. Comprehensive approaches were used to develop new risk cross sections and the extension of these into recommendations for risk assessment during space missions. The methodology relies on published data generated and the extensive research initiative managed by the NASA Human Research Program (HRP) and reviewed by the National Academy of Sciences. This resulted in recommendations for revised specifications of quality factors, $Q_{NASA}(Z,\beta)$ in terms of track structure concepts that extend beyond LET alone. The new paradigm for quality factors placed demands on radiation monitoring procedures that are not satisfied by existing dosimetry systems or particle spectrometers that are practical for space exploration where mass, volume, band width and power consumption are highly constrained. We have proposed a new definition of quality factors that relaxes the requirements for identifying charge, Z, and velocity, β, of the incident radiation while still preserving the functional form of the inherent risk functions. The departure from the exact description of $Q_{NASA}(Z,\beta)$ is that the revised values are new functions of LET for solid cancers and leukemia. We present the motivation and process for developing the revised quality factors. We describe results of extensive simulations using GCR distributions in free space as well as the resulting spectra of primary and secondary particles behind aluminum shields and penetration through water. In all cases the revised dose averaged quality factors agreed with those based on the values obtained using $Q_{NASA}(Z,\beta)$. This provides confidence that emerging technologies for space radiation dosimetry can provide real time measurements of dose and dose equivalent while satisfying constraints on size, mass, power and bandwidth. The revised quality factors are sufficiently generalized to be applicable to radiation protection practices beyond space exploration.

1. Introduction

Systems for radiation protection from occupational exposure to ionizing radiation must include a methodology to optimize constraints that keep individual exposures as low as reasonably achievable (ALARA) and insure that the combination of all efforts will not result in radiation risks that are judged to be unacceptable (International Commission on Radiological Protection, 1977). The ICRP has recognized that the general systems of radiation protection of workers on earth are not appropriate for astronauts exposed to environmental radiations during manned space missions (International Commission on Radiological Protection, 2007; International Commission on Radiological Protection, 2013). One significant issue is the large contribution of high energy, heavy charged particles (HZE) which necessitates the determination of radiation quality factors rather than radiation weighting factors, w_R. NASA has established guidance for both acute effects that might cause performance degradation or sickness resulting from high intensity solar particle events (SPE) and late effects related to the incidence and possible mortality of cancer from continuous long term exposure to galactic cosmic rays (GCR). The current permissible exposure limit (PEL) for astronauts corresponds to a 3% risk of exposure-induced death (REID) evaluated at the 95% confidence level (NASA, 2007; National Council on Radiation Protection and Measurements, 2000).

New models for radiological risk assessment have been proposed that include significant revisions based on new epidemiological data and radiation biology results that indicate RBE differs for leukemia and solid tumors. Extensive computational approaches were used to develop new risk cross sections and the extension

* Correspondence to: 1618 Campus Delivery, Colorado State University, Ft. Collins, CO 80523, United States. Tel.: +1 (970) 491 6450.
E-mail address: tborak@colostate.edu (T.B. Borak).

http://dx.doi.org/10.1016/j.lssr.2014.02.005

of these into recommendations for risk assessment during space missions (Cucinotta et al., 2013). The methodology is based on published results generated by the comprehensive research program that was managed by the NASA Human Research Program (HRP) which conducts research and develops technologies that allow humans to travel safely and productively in the environment of space.

In 2011, the National Research Council (NRC) Space Science Board of the National Academy of Sciences began a review of the NASA Model by a panel of experts in the areas of space physics, radiobiology, epidemiology, and risk assessment. The technical evaluation of the NASA model for cancer risks to astronauts due to space radiation was published in 2012 (National Research Council, 2012).

This resulted in recommendations for revised specifications of quality factors, Q, in terms of track structure concepts that extend beyond LET alone and revised estimates of DDREF. The new paradigm for determining quality factors places demands on radiation monitoring procedures that are not satisfied by existing dosimetry systems or particle spectrometers suitable for space exploration. In effect, instrumentation would be required to measure the charge, Z, and velocity, β, of the complete fluence spectrum of heavy charged particles in the galactic cosmic ray continuum $\Phi(Z,\beta)$ generally specified as $\frac{dN(Z,E)}{dE\,d\Omega\,dt}$ where $dN(Z,E)$ is the multiplicity of particle with charge Z and energy E (MeV/n) per cm^2 specified for intervals of energy dE, solid angle $d\Omega$, and time dt.

We have proposed a new definition of quality factors that relaxes the constraint of differentiating charge and velocity while still preserving the functional form of the inherent risk functions that are influenced by relative biological effectiveness and track structure. The departure from the exact description of Q is that the revised values are new functions of LET for solid cancers and leukemia.

We present the motivation and process for developing the new quality factors and the results of extensive tests using GCR distributions in free space as well as the resulting spectrum of primary and secondary particles behind aluminum shields and penetration through water. In all cases the revised dose averaged quality factors agreed with those based on the values originally proposed by NASA. This provides confidence that emerging technologies for space radiation dosimetry can provide real time measurements of dose and dose equivalent while satisfying constraints on size, mass, power and bandwidth.

2. Background

To the first approximation, there is a phenomenological relationship between radiation quality and RBE, which is defined in terms of absorbed dose.

$$RBE = \frac{D_\gamma}{D_L} \propto \frac{\alpha_L}{\alpha_\gamma} \tag{1}$$

where α represents the slope of the linear portion of the dose response curve for reference photons (γ) and heavy charged particles (L).

For convenience in radiation protection, the concept of RBE was introduced through the quantity of dose equivalent, H, that correlates to the detrimental effects of stochastic late effects. H is defined as the dose at the point of interest, D, multiplied by an RBE based Quality Factor, Q (International Commission on Radiological Protection, 1977). This was later modified to form an equivalent dose, $H_{T,R}$, which is the dose averaged over a tissue or organ, D_T, multiplied by a radiation weighting factor, w_R for radiation of type, R (International Commission on Radiological Protection, 1990). The ICRP provided a table for recommended radiation weighting factors for common types of radiation but concluded that for applications in space, where high energy charged particles contribute significantly to the total dose in the human body, a more realistic approach may have to be used (International Commission on Radiological Protection, 1990). For mission planning and operations, NASA uses the model recommended by the NCRP to estimate cancer risks from space LET-dependent radiation quality factors, $Q(LET)$ to estimate organ dose equivalents.

Another approach for characterizing radiation quality for penetrating charged particles is to introduce risk or action cross sections, σ, which express the risk per unit fluence (Curtis et al., 1992; National Council on Radiation Protection and Measurements, 2001). Biophysical models applied to these cross sections provided a more consistent and accurate description of risks for a large variety of radiations and biological end points (Curtis et al., 1992).

NASA has adopted the biophysical approach and developed a risk cross section for carcinogenesis, $\Sigma(Z,E)$, for GCR radiations with atomic number, Z, and energy per nucleon, E (Cucinotta et al., 2013).

$$\Sigma(Z,E) = \Sigma_0 \cdot P(Z,E) + \frac{\alpha_\gamma \cdot LET}{6.24} \cdot \big(1 - P(Z,E)\big), \tag{2}$$

where

$$P(Z,E) = \Big(1 - e^{\frac{-(Z^*/\beta)^2}{\kappa}}\Big)^m \cdot P_{\mathrm{TD}} \tag{3}$$

$$Z^* = Z\Big(1 - e^{-\left(\frac{1.25\cdot\beta}{Z^{2/3}}\right)}\Big) \tag{4}$$

$$P_{\mathrm{TD}} = \Big(1 - e^{-\left(\frac{E}{E_{\mathrm{TD}}}\right)}\Big) \tag{5}$$

The parameter m is the slope of the cross section representing the increase in RBE as the ionization density increases. κ determines the location of the maximum value of RBE and then begins to decline due to saturation effects of increasing ionization density. The quantity Z^* in Eq. (4) represents the reduced charge of the positive ions as they reach low velocities. P_{TD} takes into consideration the decrease in the radial dimensions, "thinning down", of a track as it nears termination (Katz et al., 1971). E_{TD} (MeV/n) in Eq. (5) is set at 0.2 based on experimental data for H and He (Cucinotta et al., 2013).

Ideally, a dosimetric approach and fluence based approach should provide similar estimates of risk, and thus:

$$D \cdot Q = \Sigma \cdot \Phi \tag{6}$$

Considering that:

$$D = \frac{LET}{\rho} \cdot \Phi \tag{7}$$

and

$$RBE = \frac{6.24}{\alpha_\gamma \cdot LET} \tag{8}$$

where the units are expressed as D (Gy), LET (keV/μm) and ρ (g/cm^3). One then obtains the following expression for the proposed NASA quality factor:

$$Q_{\mathrm{NASA}} = \big(1 - P(Z,E)\big) + \frac{6.24(\Sigma_0/\alpha_\gamma)}{LET} \cdot P(Z,E) \tag{9}$$

This constitutes a hybrid approach where absorbed dose is modified by a fluence-based biophysical model for Q_{NASA}.

Implementation of this approach using Eqs. (3), (4), (5) and (9) will introduce significant challenges to the development of instrumentation and data processing. Table 1 is a summary of the parameters that need to be included either by derivation from the model or real-time measurements in space. The coefficients can be applied off line and include values for solid tumors and leukemia,