Life Sciences in Space Research 5 (2015) 31–38

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

Safe days in space with acceptable uncertainty from space radiation exposure

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ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 6 April 2015
Accepted 7 April 2015

Keywords:
Galactic cosmic rays
HZE particles
High LET radiation
Space radiation
Cancer risk
Relative biological effectiveness
Quality factors

ABSTRACT

The prediction of the risks of cancer and other late effects from space radiation exposure carries large uncertainties mostly due to the lack of information on the risks from high charge and energy (HZE) particles and other high linear energy transfer (LET) radiation. In our recent work new methods were used to consider NASA's requirement to protect against the acceptable risk of no more than 3% probability of cancer fatality estimated at the 95% confidence level. Because it is not possible that a zero-level of uncertainty could be achieved, we suggest that an acceptable uncertainty level should be defined in relationship to a probability distribution function (PDF) that only suffers from modest skewness with higher uncertainty allowed for a normal PDF. In this paper, we evaluate PDFs and the number or "safe days" in space, which are defined as the mission length where risk limits are not exceeded, for several mission scenarios at different acceptable levels of uncertainty. In addition, we briefly discuss several important issues in risk assessment including non-cancer effects, the distinct tumor spectra and lethality found in animal experiments for HZE particles compared to background or low LET radiation associated tumors, and the possibility of non-targeted effects (NTE) modifying low dose responses and increasing relative biological effectiveness (RBE) factors for tumor induction. Each of these issues skew uncertainty distributions to higher fatality probabilities with the potential to increase central values of risk estimates in the future. Therefore they will require significant research efforts to support space exploration within acceptable levels of risk and uncertainty.

1. Introduction

Space radiation protection methods are derived largely from ground based methods recommended by the National Council on Radiation Protection and Measurements (NCRP) (NCRP, 1993) or International Commission on Radiological Protections (ICRP) (ICRP, 1990). Radiation protection is built on the principles of risk justification, limitation and ALARA (As Low As Reasonably Achievable). However because of the large uncertainties in HZE particle radiobiology and the small population of space workers, distinct methods are used at NASA to implement a radiation protection program. The basic approach is derived from recommendations by the NCRP (NCRP, 1989, 2000, 2014), however in a series of developments over the last 15 years methods to implement uncertainty analysis have been developed, undergone external review by the National Research Council (NRC) (NRC, 2008, 2012), NCRP (NCRP, 2014) and through peer-review publications (Cucinotta et al., 2001, 2006, 2013a, 2013b; Cucinotta, 2014, 2015), and implemented by NASA. Future focus on uncertainty reduction in risk predictions is considered in this paper.

In our recent work (Cucinotta et al., 2013b; Cucinotta, 2014, 2015) several methods were introduced and shown to reduce overall space mission risk predictions or uncertainties: 1) particle track structure concepts were used to formulate a space radiation quality factor (QF) function that is dependent on particle charge number, Z and kinetic energy per atomic mass unit, E with QF uncertainties where represented by subjective probability distribution functions (PDF), 2) A QF model was formulated, denoted $QF_{\gamma Acute}$ with QFs defined relative to acute γ-ray doses (0.5 to 3 Gy) based on RBE and dose and dose-rate effectiveness factor (DDREF) data for solid tumors in several strains of mice, 3) Distinct QFs for solid cancers and leukemia risk were introduced with lower values for the latter, and 4) a never-smoker population model was introduced to represent astronauts and shown to reduce risks by about 30% compared to the U.S. Average population. Other results showed possible increases in space radiation risks including: 1) additional

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http://dx.doi.org/10.1016/j.lssr.2015.04.002

risks for circulatory disease and central nervous system (CNS) effects (Cucinotta et al., 2013a, 2014), 2) the potential of increased tumor lethality for high LET particles (Cucinotta, 2014, 2015), and 3) the distinct mechanisms and dose response from non-targeted effects (NTE) that may alter low dose and chronic irradiation prediction. In this paper, we consider the number of safe days in space where risks and uncertainties are below NASA's limits in light of these recent developments.

In addition an important issue that has not been discussed in detail is the definition of an acceptable level of uncertainty (ALU). Without this definition safety programs could be burdened by unrealistic expectations on the accuracy of risk projections. The focus of the current paper is to consider the ultimate outcome of such research, whereby reaching a zero level of uncertainty (ZLU) is deemed not possible, and the definition of an ALU becomes crucial. The current approach is to consider the 95% confidence interval (CI) which is consistent with biomedical research standards on significance. However, NASA's Strategic Plan for Radiation Research from 1998 (Strategic, 1998) defined a 50% uncertainty level as the goal of research. In this paper we compared different methods to test risk predictions with their current levels of uncertainty. We suggest that the ideal case is a risk estimate that has all three of the following three attributes: 1) a central estimate below the REID limit, 2) an overall PDF for the REID prediction that follows a normal distribution in shape, and 3) the 95% confidence level of the PDF is no more than 50% above the REID limit. In this approach the radiobiological factors that cause the large skewness observed in current risk predictions to higher REID values are the main issue to be addressed by research studies. We consider various definitions of an acceptable uncertainty level in relationship to the number of "safe days" in space (defined as days to reach exposure limits) for typical shielding amounts for GCR exposure at a deep solar minimum (taken as the 2009 space environment) and for the average solar modulation of GCR using our recently published NASA Space Cancer Risk, NSCR-2014 model (Cucinotta, 2014, 2015), which is an update of our earlier NSCR-2012 model (Cucinotta et al., 2013a). Finally, we briefly review the major issues that make the current estimates highly skewed towards unacceptable REID values.

2. Methods

We briefly summarize recent methods developed to predict the risk of exposure induced death (REID) for space missions and associated uncertainty distributions (Cucinotta et al., 2013a, 2013b; Cucinotta, 2014, 2015). The instantaneous cancer incidence or mortality rates, λ_I and λ_M, respectively, are modeled as functions of the tissue averaged absorbed dose D_T, or dose-rate D_{Tr}, gender, age at exposure a_E, and attained age a or latency L, which is the time after exposure $L = a - a_E$. The λ_I (or λ_M) is a sum over rates for each tissue that contributes to cancer risk, λ_{IT} (or λ_{MT}). These dependencies vary for each cancer type that could be increased by radiation exposure. The total risk of exposure induced cancer (REIC) is calculated by folding the instantaneous radiation cancer incidence-rate with the probability of surviving to time t, which is given by the survival function $S_0(t)$ for the background population times the probability for radiation cancer death at previous time, summing over one or more space mission exposures, and then integrating over the remainder of a lifetime (United Nations Scientific Committee on the Effects of Atomic Radiation, 2008):

$$REIC(a_E, D_T) = \sum_{j=1}^{N_m} \int_{a_{Ej}} dt \lambda_{Ij}(a_{E_j}, t, D_{Tj}) S_0(t) \times e^{-\sum_{k=1}^{Nm} \int_{a_E}^{t} dz \lambda_{M_k}(a_{E_k}, z, D_{Tk})} \quad (1)$$

where z is the dummy integration variable. In Eq. (1), N_m is the number of missions (exposures), and for each exposure, j, there is a minimum latency of 5-years for solid cancers, and 2-years for leukemia assumed. Tissue specific REIC estimates are similar to Eq. (1) using the single term from λ_I of interest. The equation for REID estimates is similar to Eq. (1) with the incidence rate replaced by the mortality rate (defined below).

The tissue-specific cancer incidence rate for an organ absorbed dose, D_T, is written as a weighted average of the multiplicative and additive transfer models, denoted as a mixture model after adjustment for low dose and dose-rates through introduction of the dose and dose-rate effectiveness factor (DDREF) and radiation quality through the space radiation QF:

$$\lambda_{IT}(a_E, a, H_T) = \left[v_T ERR_T(a_E, a) \lambda_{0IT}(a) + (1 - v_T) EAR_T(a_E, a) \right] \times \frac{QF \bullet D_T}{DDREF} \quad (2)$$

where v_T is the tissue-specific transfer model weight, λ_{0IT} is the tissue-specific cancer incidence rate in the reference population, and where ERR_T and EAR_T are the tissue specific excess relative risk and excess additive risk per Sievert, respectively. The tissue specific rates for cancer mortality λ_{MT} are modeled following the BEIR VII report (BEIR VII, 2006) whereby the incidence rate of Eq. (2) is scaled by the age, sex, and tissue specific ratio of rates for mortality to incidence in the population under study:

$$\lambda_{MT}(a_E, a, H_T) = \frac{\lambda_{0MT}(a)}{\lambda_{0IT}(a)} \lambda_{IT}(a_E, a, H_T) \quad (3)$$

The U.S. cancer rates from 2011 as represented by the DEVCAN software (Version 6.7.2) available from the Center of Disease Control (CDC) are used in this report (DevCan, 2014). DEVCAN provides age, sex and tissue specific incidence and mortality data to ages 95+. Corrections for never-smokers for cancer and circulatory risks were made as described previously (Cucinotta et al., 2013a, 2012).

Risks of circulatory diseases were made in the same manner as our previous reports (Cucinotta et al., 2013b; Cucinotta, 2014). Circulatory disease risks included cardiovascular disease (CVD) and ischemic heart disease (IHD) using excess relative risk (ERR) estimates from a recent meta-analysis of studies of atomic bomb survivors, and nuclear workers in several countries (Little et al., 2012). Circulatory disease risk estimates were made using the dose equivalent for the blood forming system (BFO) based on the distinct deterministic effects relative biological effectiveness (RBE) factor compared (NCRP, 2000) to that of cancer estimates, and without the use of a dose and dose-rate reduction effectiveness factor (DDREF) because the meta-analysis is based largely on chronic exposures. For circulatory disease risks because the RBE is distinct from the quality factor (QF), organ dose equivalents are expressed in terms of a different unit, Gray-Equivalent (Gy-Eq) (NCRP, 2000).

The QF function divided by the DDREF is modeled as being made-up of two terms in the NSCR-2012 model (Cucinotta, 2015):

$$\frac{QF(Z, E)}{DDREF} = \frac{Q_{low}(Z, E) + Q_{high}(Z, E)}{DDREF} \quad (4)$$

In Eq. (4) Q_{high} and Q_{low} roughly represent the contributions from a particle track acting in high density (track core) or low density modes (track penumbra), respectively with the radiosensitivity parameters described below defining these relative contributions. Parameters are estimated from available RBE_{max} data for mouse tumor induction or surrogate endpoints in cell culture models as described previously (Cucinotta et al., 2013a).

The NSCR-2014 model QF makes an assessment of QFs based on RBEs determined from low dose and dose-rate particle data relative to acute γ-ray from experiments for doses of about 0.5 to 3 Gy denoted as $RBE_{\gamma Acute}$ which was suggested by Edwards (1999).