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ORIGINAL ARTICLE

Computer-Assisted Formulas Predicting Radiation-Exposure-Induced-Cancer Risk in Interplanetary Travelers: Radiation Safety for Astronauts in Space Flight to Mars

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A clear quantitative relationship between the dose of total body ionizing radiation and mortality in humans is not known because of lack of human data that would enable us to determine the lethal dose for 50% of cases (LD_{50}) in total body irradiation on earth or in probable future interplanetary travels. Analysis of human data has been primarily from radiation accidents, radiotherapy, and the atomic bomb victims. The author published the general mathematical formula that predicts mortality probability as a function of dose rate and duration of exposure to acute ionizing radiation in humans on the basis of data presented by Cerveny *et al.*, employing the author's mathematical probacent model. Further, the author applied the general formula to the data on dose versus cancer mortality risk published by the United Nations Scientific Committee on the effects of atomic radiation and other investigators to construct general formulas expressing a relationship between dose and solid cancer or leukemia mortality probability after exposure to acute low-dose ionizing radiation in humans on earth. There is a remarkable agreement between formula-derived and published values of dose and solid cancer or leukemia mortality probability ($P > 0.99$). In this study, the above mortality formulas are applied to the measurements of the Mars Science Laboratory spacecraft containing the Curiosity rover (2012–2013) in estimating radiation safety for astronauts in a future space flight to Mars planned by the National Aeronautics and Space Administration. Results of the estimation obtained with a mathematical approach are presented in this study.

Key words: Formula of LD_{50}, probacent model, radiation safety in interplanetary travelers, radiation-exposure-induced-cancer mortality, space flight to Mars, theory of everything, ultron-logotron theory

INTRODUCTION

A clear quantitative relationship between the dose of radiation and mortality in humans is not known because of lack of human data that would enable us to determine LD_{50} for humans in total body irradiation. Analysis of human data has been primarily from radiation accidents, radiotherapy, and the atomic bomb victims.

Consequently, laboratory animals have been used to investigate the relationship between radiation exposure and biomedical effects in total body irradiation and further to possibly derive a general mathematical formula expressing a dose-effect curve.[1-4]

GENERAL MATHEMATICAL MODEL OF PROBACENT-PROBABILITY EQUATION

A mathematical model of the "probacent"-probability equation, equation (1) was developed on the basis of animal experiments, clinical application, and mathematical reasoning to express a relationship among intensity of stimulus, duration of exposure and response in biological phenomena.[5-9]

$$\mathrm{P} = [(i-a)\, t^n - c]/(b\, t^n + d) \tag{1a}$$

$$\mathrm{Q} = \frac{10}{\sqrt{(2\pi)}} \int_{-\infty}^{p} \exp\ [-(p-50)^2/200]\, dP \tag{1b}$$

where i is intensity of stimulus, external stressor or noxious agent; t is duration of exposure; a, b, c, d and n are constants. P is "probacent" (abbreviation of percent probability), a relative amount of internal stress caused by an external stressor or a relative amount of loss of reserve for survival. Probacent values of 0, 50, and 100 correspond to (mean-5 standard deviation [SD]), mean and (mean + 5 SD), respectively; the

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unit of "probacent" is 0.1 SD In addition, 0, 50, and 100 probacents seem to correspond to 0, 50, and 100 percent probability, respectively, in mathematical prediction problems in terms of percentage. Q is mortality probability (%). Survival probability (%) is (100-Q). Equation (1) can be used for survival probability problems.

The probacent model has been applied to data in biomedical literature to express a relationship among plasma acetaminophen concentration, time after ingestion, and occurrence of hepatotoxicity in man;[10] to express survival probability in patients with heart transplantation;[11] to express survival probability in patients with malignant melanoma;[12] to express a relationship among blood levels of carboxyhemoglobin as a function of carbon monoxide concentration in air and duration of exposure,[13] and to express a relationship among age, height, and weight, and percentile in Saudi and US children of ages 6–16 years.[14]

The equation of death rate of the probacent model was applied to predict age-specific death rate in the US elderly population, 2001[7] and to express the relationship between dose rate and survival probability in total body irradiation in humans.[8,9] The results of the above two studies revealed a close agreement between "probacent"-formula-derived and published-reported values of death rates in humans or survival probability in humans ($P > 0.995$).

Mehta and Joshi[15] successfully applied the probacent-probability equation model to use model-derived data as an input for radiation risk evaluation of the Indian adult population in their studies.

Formulas expressing a relationship among dose rate, duration of exposure, and mortality probability in total body irradiation in humans

A general formula was developed on the basis of the animal-model predictions of lethal radiation doses for humans published by Cerveny, *et al.*[1] The data are based on the extensive study of mortality resulting from radiation exposure and a compilation of animal experimental data published by Jones, Morris, Wells, and Young at the Oak Ridge National Laboratory.[2] The LD_{50} for humans is mathematically predictable as a function of dose rate and duration of exposure. A remarkable agreement is present between values of formula-derived and animal-model-predicted LD_{50} as well as mortality probabilities ($P > 0.995$).

The probacent model was applied to the data on dose versus solid cancer or leukemia mortality probabilities published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR,) and other investigators[16,17,44,45] to construct general formulas expressing between dose and solid cancer or leukemia mortality probability after exposure to acute low-dose ionizing radiation in humans.[18] There is a remarkable agreement between formula-derived and published values of dose and solid cancer or leukemia mortality probability ($P > 0.99$). The general formula might be helpful in preventing radiation hazard and injury in acute low-dose ionizing radiation, and for safety in radiotherapy and further in case of astronauts in a possible future long space flight to Mars by mathematically estimating their safety.[19]

Space radiation in transit to Mars

Zeitlin *et al.*[20] reported the measurements of energetic particle radiation made by the Radiation Assessment Detector (RAD) inside Mars Science Laboratory (MSL) spacecraft in transit to Mars (2011–2013). The RAD provides the data on the measurements of the radiation dose, dose equivalent, and linear energy transfer spectra. The dose equivalent for the shortest round trip with current propulsion system and comparable shielding is found to be 0.66 ± 0.12 sievert [Table 1].

Radiation on Mars

Hassler *et al.*[21] reported the measurements made by RAD on MSL's Curiosity rover (2012–2013). The measurements provide the data on the absorbed dose and dose equivalent from galactic cosmic rays and solar energetic particles on the surface of Mars that are 0.21 ± 0.04 mGr/day and 0.64 ± 0.12 mSv/day, respectively [Table 1]. We receive an average of 2 mSv/year from background radiation alone on Earth; 1 mSv of space radiation is approximately equivalent to receiving three chest X-rays.[22]

Cancer risk from exposure to galactic cosmic rays in space flight

Cucinotta and Durante[23] reported that the oncogenic biological effects of high-energy ions in space radiation are poorly understood and an important barrier to exploration of Mars. The magnitude of cancer risk posed by exposure to radiation in space is subject to many uncertainties. The authors presented a review of recent worldwide research on oncogenic effects of galactic cosmic rays.

Table 1: Radiation environment measured by Mars Science Laboratory/Radiation Assessment Detector (2012–2013) (galactic cosmic rays only)

RAD measurement	MSL cruise	Mars surface	Units
Dose rate	0.48 ± 0.08	0.21 ± 0.04	mGy/day
Dose-equivalent rate	1.84 ± 0.30	0.64 ± 0.12	mSv/day
Total mission dose equivalent (NASA design reference mission)	662 ± 108 (2x180 days)	320 ± 50 (500 days)	mSv

To my knowledge, there seems to be no general mathematical models in the literature that express the quantitative relationship among dose rate, duration of exposure, and cancer mortality risk after exposure to total body ionizing radiation. The author employs a mathematical approach to estimate radiation-exposure-induced-cancer death (REID) and radiation safety in the analysis of the measurements of the Curiosity rover of MSL spacecraft (2012–2013).

The purpose of this study is to examine radiation hazards and safety in interplanetary travelers, especially for astronauts in a future space flight to Mars, applying the author's computer-assisted formulas of REID.

MATERIAL AND METHODS

Materials

Zeitlin *et al.*[20] at Johnson Space Center, USA, Southwest Research Institute, USA, Christian Albrechts University, Germany, Jet Propulsion Laboratory, USA, German Aerospace Center, National Aeronautics and Space Administration (NASA) Headquarter and other institutes, reported that MSL spacecraft, containing the Curiosity rover launched to Mars on 26 November 2011 provided detailed measurements of energetic particle radiation environment inside the RAD, the radiation dose, dose equivalent, and dose rate.

Hassler *et al.*[21] reported the measurements of the absorbed dose and dose equivalent from galactic cosmic rays and solar energetic particles on the Mars surface for up to 300 days of observations provided by MSL (2012–2013).

The measurements of both reports are shown in Table 1 and used in this study to analyze radiation hazard and safety in the exploration of Mars.

Methods

Equations

In this study, equations (2) and (3) in the author's previous publication[18] are used to express the mortality probability (Q) of solid cancer and leukemia as a function of lethal dose (D) of radiation after exposure to acute low dose ionizing radiation in humans, respectively.

$$P^{2.425} = 34.25^{2.425} - 1.96995 \times (34.25^{2.425} - 16^{2.425}) + 0.65665 \times (34.25^{2.425} - 16^{2.425}) \times \log D \qquad (2a)$$

$$Q = \frac{10}{\sqrt{(2\pi)}} \int_{-\infty}^{p} \exp\ [-(p-50)^2/200]\ dP \qquad (2b)$$

Where D = dose of radiation in mSv, P = probacent, and Q = solid cancer mortality probability (%).

$$P^{1.47} = 25.875^{1.47} - 1.996995 \times (25.875^{1.47} - 7.95^{1.47}) + 0.65665 \times (25.875^{1.47} - 7.95^{1.47}) \times \log D \qquad (3a)$$

$$Q = \frac{10}{\sqrt{(2\pi)}} \int_{-\infty}^{p} \exp\ [-(p-50)^2/200]\ dP \qquad (3b)$$

Where D = dose in mSv, P = probacent, and Q = leukemia mortality probability (%).

The equations (2) and (3) are postulated to be applicable in case of use of millisylvert (mSv) unit, dose equivalent instead of milligray (mGy) unit.

Description of computer program

Computer programs are written in UBASIC to calculate equations. The computer program uses a formula of approximation instead of integral of equations (2b) and (3b) because the computer cannot perform integral.[6,18,24] Calculation of equation (2)-(6) is carried out with the author's computer programs as shown in Figures 1 and 4.

Statistical analysis

A Chi-square goodness-of-fit test (logrank test) is used to test the fit of mathematical model to the data on dose versus mortality probability in acute ionizing radiation in humans.[9,18] The differences are considered statistically significant when $P < 0.05$.

RESULTS

Radiation-exposure-induced-solid-cancer death

Table 2 shows the results of solid cancer mortality risk in percentage as a function of dose after exposure to acute

```
10   lprint "RELATIONSHIP BETWEEN DOSE AND CANCER MORTALITY RISK"
20   D=1.84
30   lprint tab(1);"D",tab(9);"Q",tab(33);"R",tab(57);"REID=Q+R"
40   read T
50   'D stands for radiation dose in mSv
60   DeffnQ=34.25^2.425-1.96995*(34.25^2.425-16^2.425) + 0.65665*(34.25^2.425
     -16^2.425)*log(D) /log(10) + 0.65665*(34.25^2.425-16^2.425)*log(T)/log(10)
70   P=DeffnQ^(1/2.425)
80   A1=0.278393
90   A2=0.230389
100  A3=0.000972
110  A4=0.078108
120  if (P-50)<0 then 130 else 160
130  X=(50-P)/sqrt(200)
140  Q=50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
150  goto 330
160  X=(P-50)/sqrt(200)
170  Q=100-50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
180  'Q stands for solid cancer mortality probability
330  DeffnR=25.875^1.47-1.96995*(25.875^1.47-7.95^1.47) + 0.65665*(25.875^1.47
     -7.95^1.47)*log(D)/log(10) +0.65665*(25.875^1.47-7.95^1.47)*log(T)/log(10)
340  P=DeffnR^(1/1.47)
350  if (P-50)<0 then 360 else 380
360  X=(50-P)/sqrt(200)
361  R=50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
370  goto 430
380  X=(P-50)/sqrt(200)
390  R=100-50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
391  'R stands for leukenia mortality probability
430  REID=Q+R
440  lprint T,Q,R,Q+R
450  goto 40
460  data 100,200,300,400,500,600,700,800,900,1000
RELATIONSHIP BETWEEN DOSE AND CANCER MORTALITY RISK
 D       Q                       R                       REID=Q+R
 100     1.257151965871675909    0.0978669765684596571   1.355018942440135566
 200     2.58826243428173789     0.2462897165635448984   2.834552150845282788
 300     3.684338843564319742 8  0.4056868401616166407   4.090025683725936383
 400     4.614904941105069517 7  0.567966606366795266    5.182871547471864783
 500     5.42584228653371017 3   0.7300465289324236989   6.155888815466133871
 600     6.146328479135721829 1  0.8905288720728121276   7.036857351208533956
 700     6.795863766784430844 8  1.0487360851779052397   7.844599851962336084
 800     7.38811816759338947 8   1.2043411654258662662   8.592459333019255744
 900     7.933059874979022695 1  1.357201817094187427    9.290261692073210122
 1000    8.438194650824465924 8  1.5072779744832624735   9.945472625307728398
```

Figure 1: Computer program for equations (4), (5), and (6) to calculate the radiation-exposure-induced-cancer death risk (mortality probability) as a function of dose rate and duration of exposure

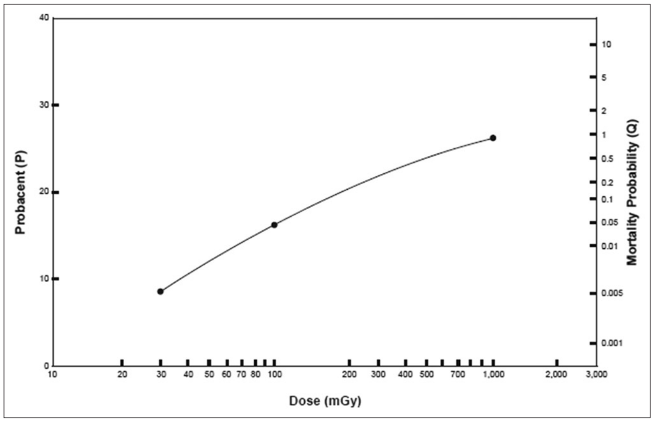

Figure 2: Relationship between dose and leukemia mortality probability of life-time risk after exposure to acute low-dose ionizing radiation in humans. The abscissa represents dose in mGy (log scale). The ordinate on the right side represents leukemia mortality probability (q) in percentage. The ordinate on the left side represents "probacent" (p) corresponding to mortality probability (q) in a lognormal probability graph. The data points of closed circles of reported-estimated leukemia mortality probabilities after exposure to 30, 100, and 1000 mGy of References 16 and 17 shown in Table 3 appear to fall on the solid-curved line representing equation (3). The other data points of reported estimated leukemia mortalities for 1000 mGy of Reference 25 in Table 3 are not plotted but if plotted would fall very close to the solid line of equation 3

low-dose total body ionizing radiation in humans. Solid cancer means excluding leukemia from total cancer developed in lifetime follow-up observations after exposure in the lifespan studies.

Table 2 also shows comparison of formula-derived values with the reported data on acute low dose versus solid cancer mortality probability (%). Both values of formula-derived and reported solid cancer mortality probabilities in Table 2 reveal a close agreement ($P > 0.99$). The maximum difference is 0.75% in exposure to 1000 mSv.

Figure 3 illustrates the relationship between dose and solid cancer mortality probability after exposure to acute low-dose ionizing radiation in humans. The closed circles of data points fall on or appear to fall close to the solid curved line expressed by equation (2). Dashed lines below and above beyond the end-points of the solid curved line of equation (2) represent extrapolation of equation (2)-expressed solid line.

Radiation-exposure-induced-leukemia death

Table 3 shows the results of leukemia mortality risk in percentage as a function of dose after exposure to acute low-dose total body ionizing radiation in humans. Comparison of both values of formula-derived and reported estimated mortality probabilities reveals a close agreement without statistical significant differences ($P > 0.995$).

Figure 2 illustrates the relationship between dose and leukemia mortality probability after exposure to acute low-dose ionizing radiation in humans. The closed circles of data points

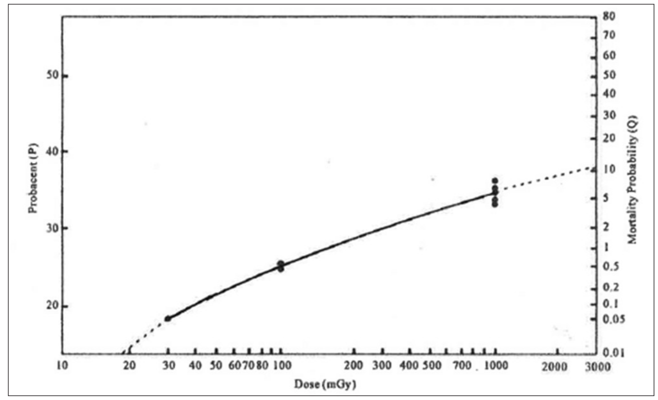

Figure 3: Relationship between dose and solid cancer mortality probability after exposure to acute low-dose ionizing radiation in humans. The abscissa represents dose in mGy (log scale). The ordinate on the left side represents "probacent" (p) corresponding to mortality probability (Q) in percentage in a lognormal probability graph. The data points of closed circles of reported-estimated solid cancer mortality probabilities after exposure to dose of 30, 100, and 10000 mGy shown in Table 2 appear to fall on or very close to the solid curved line representing equation (2)

Table 2: Relationship between dose and solid cancer mortality probability after exposure to acute low-dose ionizing radiation in humans

Acute low dose (mGy)	Formula-derived solid cancer mortality probability (%)	Reported solid cancer mortality probability (%)	Source	
			Country	Reference
30	0.05	0.05	United Kingdom	[17]
100	0.565	0.565	United Nations	[16]*
100	0.565	0.5	IAEA**	[44]
1000	5.75	5.75	United Nations	[16]*
1000	5.75	5.16	China	[25]
1000	5.75	6.40	Japan	[25]
1000	5.75	5.60	Puerto Rico	[25]
1000	5.75	5.80	United States	[25]
1000	5.75	5.81	United Kingdom	[25]
1000	5.75	5	France	[45]
		$P^{***} > 0.99$		

*Report of the United Nations Scientific Committee on the Effects of Atomic Radiation 2010 (UNSCEAR 2010); **IAEA: The International Atomic Energy Agency; P^{***}: p value in χ^2 goodness-of-fit test

Table 3: Relationship between dose and leukemia mortality probability after exposure to acute low-dose ionizing radiation in humans

Acute low dose (mGy)	Formula-derived leukemia mortality probability (%)	Reported solid leukemia mortality probability (%)	Source	
			Country	Reference
30	0.005	0.005	United Kingdom	[17]*
100	0.04	0.04	United Nations	[16]**
1000	0.8	0.8	United Nations	[16]**
1000	0.8	0.84	China	[25]
1000	0.8	0.86	Japan	[25]
1000	0.8	0.83	Puerto Rico	[25]
1000	0.8	0.85	United States	[25]
1000	0.8	0.86	United Kingdom	[25]
		$P^{***} > 0.995$		

*Report of the Health Protection Agency of the United Kingdom; **Report of the United Nations Scientific Committee on the Effects of Atomic Radiation 2010 (UNSCEAR 2010); ***p value in χ^2 goodness-of-fit test

of Reference 16, 17, and 25 in Table 3 are the basis on which equation (3) is constructed. There is a close agreement between formula-derived and reported lethal radiation doses ($P > 0.995$).

The data points on which equation (3) are based fall on the solid curved line. The other points of Reference 25 in Table 3 are not plotted in Figure 2 but, if plotted, would fall very close to the solid curved line at 1000 mSv expressed by equation (3).

Radiation-exposure-induced-cancer death

REID ($Q_{REID)}$ is equal to the sum of radiation-exposure-induced-solid-cancer death (REISCD) (Q_{REISCD}) + radiation-exposure-induced-leukemia death (REILD) (Q_{REILD}). Therefore, equations (4), (5), and (6) are newly constructed to express REID as a function of dose rate and duration of exposure in total body ionizing radiation in humans.

$$P^{2.425} = 34.25^{2.425} – 1.96995 \times (34.25^{2.425} – 16^{2.425}) + 0.65665 \times (34.25^{2.425} – 16^{2.425}) \times \log D + 0.65665 \times (34.25^{2.425} – 16^{2.425}) \times \log T \quad (4a)$$

$$Q_{\text{REISCD}} = \frac{10}{\sqrt{(2\pi)}} \int_{-\infty}^{p} \exp\ [-(p-50)^2/200]\ dP \quad (4b)$$

Where D = dose rate (mSv/min), T = duration of exposure (minute), P = probacent and Q_{REISCD} = mortality probability of REISCD.

$$P^{1.47} = 25.875^{1.47} – 1.96995 \times (25.875^{1.47} – 7.95^{1.47}) + \text{o. }65665 \times (25.875^{1.47} – 7.95^{1.47}) \times \log D + 0.65665 \times (25.875^{1.47} - 7.95^{1.47}) \times \log \mathrm{T} \quad (5a)$$

```
 10   lprint "RELATIONSHIP BETWEEN DOSE AND CANCER MORTALITY RISK"
 20   lprint "AFTER EXPOSURE TO ACUTE LOW DOSE RADIATION IN HUMANS"
 25   lprint tab(1);"D",tab(9);"Q",tab(33);"R",tab(57);"REID=(Q+R)"
 40   read D
 50   'D stands for radiation dose in mSv
 60   DeffnQ=34.25^2.425-1.96995*(34.25^2.425-16^2.425)+0.65665*(34.25^2.425
      -16^2.425)*log(D)/log(10)
 70   P=DeffnQ^(1/2.425)
 80   A1=0.278393
 90   A2=0.230389
100   A3=0.000972
110   A4=0.078108
120   if (P-50)<0 then 130 else 160
130   X=(50-P)/sqrt(200)
140   Q=50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
150   goto 330
160   X=(P-50)/sqrt(200)
170   Q=100-50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
180   'Q stands for solid cancer mortality probability
330   DeffnR=25.875^1.47-1.96995*(25.875^1.47-7.95^1.47)+0.65665*(25.875^1.47-
340   P=DeffnR^(1/1.47)
350   if (P-50)<0 then 360 else 380
360   X=(50-P)/sqrt(200)
361   R=50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
370   goto 430
380   X=(P-50)/sqrt(200)
390   R=100-50/(1+A1*X+A2*X^2+A3*X^3+A4*X^4)^4
391   'R stands for leukenia mortality probability
430   REID=Q+R
440   lprint D,Q,R,REID
450   goto 40
460   data 30,100,1000
470   data 389,390,391,392,393,662,72
RELATIONSHIP BETWEEN DOSE AND CANCER MORTALITY RISK
AFTER EXPOSURE TO ACUTE LOW DOSE RADIATION IN HUMANS
 D       Q                       R                       REID=(Q+R)
 30      0.0499827999047218154   0.0050092941753312326   0.0549920940800530481
 100     0.565105050168922324    0.0401173659508529829   0.605222416119775307
 1000    5.7488969088216746058   0.8000685417746965633   6.5489654505963711692
 389     2.7237474117183385631   0.2641594901888472526   2.9879069019071858158
 390     2.7301248899668690933   0.2650133080433770001   2.9951381980102460935
 391     2.7364957274736344044   0.2658673744627783833   3.0023631019364127877
 392     2.7428599376187206813   0.2667216878241440365   3.0095816254428647178
 393     2.7492175337596306334   0.2675762465143889973   3.0167937802740196308
 662     4.2571380024187184334   0.5026077085375802266   4.7597457109562986601
 72      0.3364054495908233679   0.0239200496510356125   0.3603254992418589804
```

Figure 4: Computer program for equations (2) and (3) to calculate the radiation-exposure-induced-cancer death risk (mortality probability) as a function of dose

$$Q_{\text{REILD}} = \frac{10}{\sqrt{(2\pi)}} \int_{-\infty}^{p} \exp\ [-(p-50)^2/200]\ dP \quad (5b)$$

Where D = dose rate (mSv/min), T = duration of exposure (minute), P = probacent and Q_{REILD} = mortality probability of REILD.

$$Q_{REID} = Q_{REISCD} + Q_{REILD} \quad (6)$$

Equation (6) can be readily calculated with the computer program shown in Figure 1.

The REISCD, REILD, and REID at the radiation dose of 30 mSv are 0.05%, 0.005%, and 0.55%; at the dose of 100 mSv, 0.565%, 0.04%, and 0.605%; at the dose of 1000 mSv, 5.75%, 0.8%, and 6.55%, respectively, as shown in the computer program [Figure 4], The REID of 391 mSv is associated with 3% of REID that is suggested to be PEL of NASA[26,27] from the standpoint of the mathematical approach. The REID of 662 mSv is 4.76%. The average effective dose for the approximately 6-month missions of the 19 astronauts of the international space station (ISS) was 72 mSv. The REID of 72 mSv is 0.36% in this study of a mathematical approach.[27]

Relationship among dose rate of 1.84 mSv/day during the round trip to Mars or 0.64 mSv/day during stay on Mars, duration of exposure, and radiation-exposure-induced-cancer death (%)

The author presents general formulas, equations **(**4), (5), and (6) that predict the relationship among dose rate of 1.84 mSv/day during the round trip to Mars or dose rate of 0.64 mSv/day during the stay on Mars, duration of exposure to radiation, and REID (%).

Table 4 shows the relationship among the durations of round trip and stay on Mars and REID in various conditions of missions. In case of the fastest round trip (240 days) and the shortest stay on Mars (100 days), its REID would be 3.65%. This REID is still >3% of NASA's PEL.

Figure 5 illustrates graphically the relationship among dose rate, duration of exposure, and REID.

Table 4: Radiation-exposure-induced-cancer death in various possible design missions to Mars

Round trip	Stay on Mars	REID
240 days (120x2)	100 day	3.65%
240 days (120x2)	360 day	5.11%
240 days (120x2)	500 day	5.83%
360 days (180x2)	100 day	5.05%
360 days (180x2)	365 day	6.51%
360 days (180x2)	500 day	7.23%

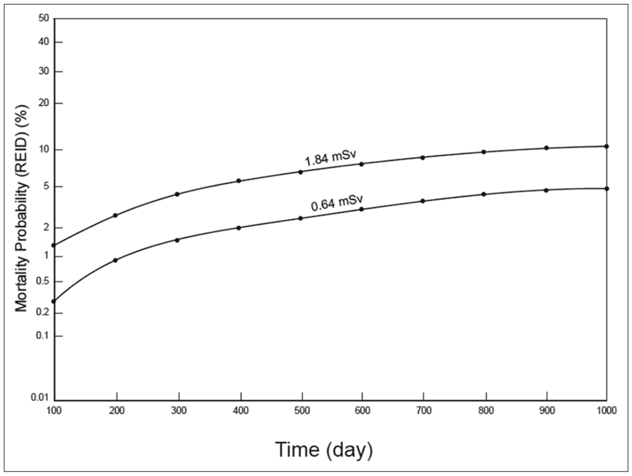

Figure 5: Relationships among dose rate of 1.84 mSv or o. 64 mSv, duration of exposure in days and radiation-exposure-induced-cancer death in total body ionizing irradiation in interplanetary space or on Mars surface. Closed circles represent values of REID at different durations of exposure, 100–1000 days in interplanetary space (1.84 mSv) or on Mars surface (0.64 mSv)

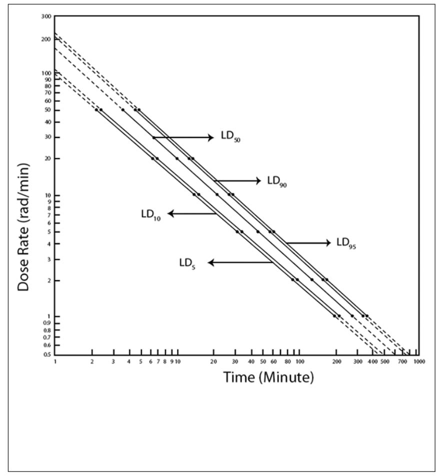

Figure 6: Relationship among dose of radiation, duration of exposure and lethal radiation dose LD_5, LD_{10}, LD_{50}, LD_{90}, and LD_{95} in total body irradiation in humans. The abscissa represents duration of exposure in minutes (log scale). The ordinate represents dose rate in rad/min (log scale). Data points indicate lethal doses of $LD_{5,\ 10,\ 50,\ 90,\ \text{and}\ 95}$ appear to fall on the five formula-predicted straight lines in each group, respectively (see text)

3% radiation-exposure-induced-cancer death

The Russian Space Agency, European Space Agency and Canadian Space Agency have adopted 1 Sv as the astronaut career exposure limit.[20] NASA proposed 3% REID risk as PEL.[26,27]

In this study with the mathematical approach and the computer program of Figure 4, the dose of 391 mSv would correspond to the NASA's PEL of 3%. The REID of 1 Sv is 6.55%.

Lethal doses of LD_3, LD_5, LD_{10}, LD_{50}, LD_{90} and LD_{95} of total body irradiation in humans.

Table 5 and Figure 6 show the relationship among dose rate of radiation, duration of exposure and lethal dose, LD_5, LD_{10}, LD_{50}, LD_{90} and LD_{95} in total body irradiation in humans.[9] Formulas of LD_5, LD_{10}, LD_{50}, LD_{90} and LD_{95} that express the above relationship are published in the author's previous publication.[9] Figure 7 illustrates LD_3 of lethal dose of 3% REID. Each of the 6 lines in both Figures 6 and 7 reveals a straight line in exposure to acute low, moderate, and high doses of ionizing radiation in humans.

Table 5: Comparison of formula-derived and animal-model-predicted lethal radiation doses to humans

Lethal Dose		Dose Rate (Gy/minute) 0.01	0.02	0.05	0.10	0.20	0.50
LD_5	Formula-Derived *	194.0	176.9	156.4	142.7	130.0	115.0
	Model-Predicted **	194	177	156	143	130	115
LD_{10}	Formula-Derived	210.0	192.3	171.3	156.9	143.8	128.0
	Model-Predicted	210	192	171	157	144	128
LD_{50}	Formula-Derived	275.0	256.6	234.1	218.4	203.9	186.0
	Model-Predicted	275	257	234	218	204	186
LD_{90}	Formula-Derived	341.0	321.1	296.7	279.3	263.1	243.0
	Model-Predicted	341	321	297	279	263	243
LD_{95}	Formula-Derived	360.0	339.1	313.4	295.2	278.1	257.0
	Model-Predicted	360	339	313	295	278	257

*Formula-derived lethal radiation doses are calculated from the five equations, (3)–(7),[1] obtaining lethal doses by dose rate (rad/min), D multiplied by duration of exposure, time T (min),[9] **Model-predicted lethal radiation doses are obtained.[9] $P > 0.995$

DISCUSSION

Tables 2, 3, and Figures 2, 3 reveal a remarkable agreement between formula-derived and reported-estimated data on solid cancer ($P > 0.99$) or leukemia ($P > 0.995$) mortalities after exposure to acute low-dose ionizing radiation in humans. This study is primarily based on the report (2010) of UNSCEAR.[16] The UNSCEAR has been undertaking reviews and evaluations of global and regional exposures to radiation and also evaluates evidence of radiation-induced health effects including cancers and deaths in exposed groups, including survivors of the atomic bombings in Japan. The UNSCEAR provides international standards for the protection of the general public and workers against ionizing radiation.[16]

A quantitative dose-response relationship in lethal ionizing radiation exposure in humans is not known.[1] Several investigators have derived hypothetical dose-response curve based on experiences with reactor accidents and the atomic exposure in Japan. From these observations, LD_{50} for humans exposed to single dose of radiation delivered over a period of less than 24 h is believed to be in the range of 2.50-4.0 Gy.[28] Levin, Young and Stohler[29] published an

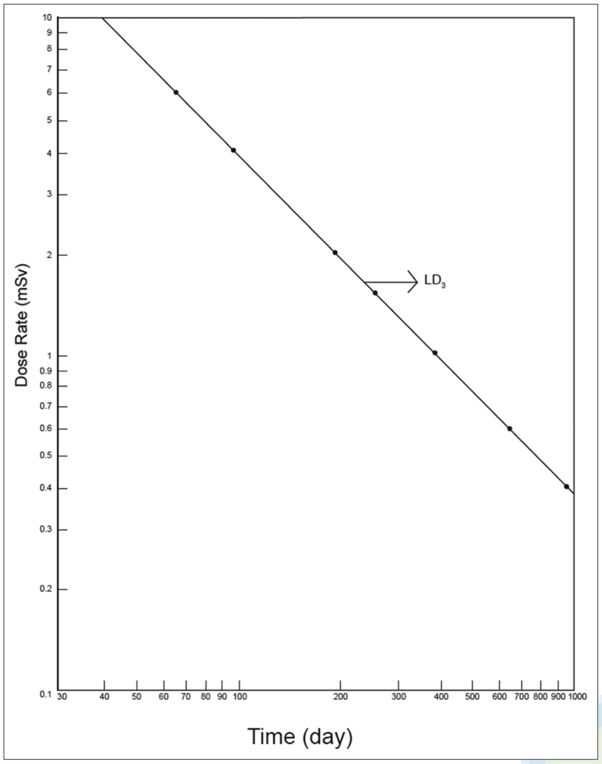

Figure 7: Relationship between dose rate and duration of exposure for 3% radiation-exposure-induced-cancer death, LD_3. The zone below the straight line represents radiation-exposure-induced-cancer death <3% radiation-exposure-induced-cancer death, and the zone above the line represents radiation-exposure-induced-cancer death >3% radiation-exposure-induced-cancer death

estimate of the median lethal dose on humans exposed to total body ionizing radiation and not subsequently treated for the radiation sickness. The median lethal dose was estimated from calculated doses to young adults who were inside two reinforced concrete buildings that remained standing in Nagasaki, Japan, after the atomic detonation. Median dose estimates were calculated using both logarithmic (2.9 Gy) and linear (3.9 Gy) dose scales. Both calculations supported previous estimates of the median lethal dose-based solely on human data, which clustered around 3 Gy. The LD_{50} of 2.9 Gy was surprisingly consistent with estimates made by other researchers; 2.45 Gy by Langham, 2.86 Gy by Lushbaugh et al, 2.65-2.70 Gy by Bond and Robertson.[29]

Fujita, Kato, and Schull[30] reported the LD_{50} of 2.3-2.6 Gy that is noticeably in a good agreement with the value of LD_{50} shown in Table 5. There is a remarkable agreement between the formula-derived LD_{50} in Table 5 and the above-described published-estimated LD_{50}.[28-30]

The dose-response relation in human exposure to ionizing radiation reveals a linear relationship in both high- and low-dose rates as shown in Figures 6 and 7 if the dose rate and duration of exposure are plotted on a log–log graph paper.

Hematopoietic cells of bone marrow, intestinal tract, and central nervous system are most vulnerable for radiation effects.[31-33]

It is the current understanding in the studies of the development of cancer after radiation exposure that the process starts by the mutation of one or more genes of the DNA of a single “stem-like” cell in a body organ contributes to cancer development unless affected cells have repaired the DNA. Body responses to radiation exposure reflect status of living body in which physiologic response, repair and regeneration of recovery, pathologic changes, and aging process are concurrently occurring.[3,28,34-36] There is a strong epidemiological evidence that exposure of humans to radiation at moderate and high levels can lead to excess incidence of solid tumors in many organs and of leukemia.[23]

Cucinotta *et al.* at NASA, Lyndon B. Johnson Space Center, Wyle Laboratory Life Science Group and U. S. R. A. Division of Space Life Sciences reported radiation damages in blood cells (lymphocytes) in the 19 astronauts of the ISS after approximately 6-month missions.[27]

Elon Musk, Chief Executive Officer of the rocket company, SpaceX, and the autopilot car company, Tesla, recently published his vision to colonize Mars and save humanity.[46] If it is real and true that a 160-day round trip to Mars, a 100-day stay on Mars surface and a 1000-day stay in the radiation-shielded building and/or the underground shelter-like gimme shelter caves with a skylight opening[47] of Mars,[48] then the REID of the planned space flight to Mars would be 2.86% with dose 371 mSv that is <3% of the NASA’s PEL of dose 391 mSv[47] in the mathematical analysis of this study (see equation **7**).

$$1.84 \times 80 \times 2 + 0.64 \times 100 + 0.0128 \times 1000 = 371 \text{ mSv} \quad (7)$$

The dose rate of radiation in the radiation-shielded building and the underground shelter of Mars is assumed to be 1/50 of the dose rate of Mars surface (1.64/50 = 0.0128). When the above-described advancements in technologies are achieved, space flights to Mars would be safe for astronauts against cosmic ray.

The probacent formula gave a special momentum to the author to develop the hypothesis of the ultron-logotron theory related to mind and matter, consciousness, and quantum physics (Theory of Everything), and further, the possible deeper structure of leptons and quarks on the basis of quantum physics and Confucian philosophy.[37,38]

It has been recently discovered that electrons split into two separable parts: A spinon (a neutral magnet behaving as a tiny compass needle) and an orbiton carrying its electron motion (negative electrical charge) around the nucleus.[38,40,41] The spinon and orbiton seem to correspond to the neutral part of yin-and yang-ultrons composite and the negative part of yin-ultron as predicted in the ultron-logotron theory, respectively. Yin-and yang-ultrons in a spinon are postulated to line up in a tiny series magnet with a south and a north pole in one direction that can generate spin. This substructure of electron suggests that a quark in a proton is likewise composed of two separable particles, a magnetic (of yin-and yang-ultrons composite), and an electrical particle (of yin-or yang-ultrons).[38,42,43]

This study regarding radiation hazards and safety in total body irradiation in humans in a space trip is based on reported data and the mathematical approach and analysis. Further, research would be needed for the verification of the findings and propositions in this study.

CONCLUSIONS

The author published a general formula that predicts mortality probability of solid cancer or leukemia death as a function of lethal dose in acute low-dose total body ionizing irradiation in humans. The formula was constructed by applying the author's general mathematical model of "probacent"-probability equation that expresses relationships among intensity of stimulus, duration of exposure, and response in biomedical phenomena. New formulas of tolerance in total body irradiation that expresses the radiation-exposure-induced-cancer death (REID) as a function of radiation dose rate and duration of exposure in total body ionizing irradiation in humans are constructed. In this study, the new formulas are applied to the measurements of the MSL spacecraft containing the Curiosity rover (2012–2013) to estimate radiation safety for astronauts in a future space flight to Mars. The following findings and conclusions in the author's mathematical approach are proposed:

1. New general equations, equation, (4) (5) and (6) that express the REID as a function of lethal dose rate and duration of exposure are constructed from both equations, equations (2) and (3) of the author's previous publication[18] that predict mortality probabilities of solid cancer death and leukemia death risk in total body irradiation in humans
2. Estimates of REID in various circumstances of missions for astronauts in space flights to Mars are calculated and shown in Table 4. In case of the fastest round trip (240 days) and the shortest stay on Mars (100 days), its REID would be 3.65%. This REID is still >3% of the NASA's permissible exposure limit (PEL)
3. A lethal dose of 391 mSv seems to correspond to the NASA's PEL 3% of REID
4. Results of this study suggest that a future space flight to Mars would need increase in propulsion power for a faster speed and a shortened round trip, and increase in protective radiation shielding to reduce radiation dose rate, and a shortened stay on Mars for the astronauts' radiation safety in a future space flight to Mars. When the above-described advancements in technologies are achieved, the space flight to Mars would be safe for astronauts against cosmic ray.

Further research would be needed for verification of the above presentations and propositions.

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Conflicts of interest

There are no conflicts of interest.

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