Space Radiation Future Directions

Honglu Wu, Ph.D.

NASA Johnson Space Center

Space Radiation Risks

- **Risk of Radiation Carcinogenesis**

–Morbidity and mortality risks

- **Risk of Acute (In-flight) & Late Central Nervous System Effects from Radiation Exposure**

–Changes in cognition, motor function, behavior and mood, or neurological disorders

- **Risk Of Cardiovascular Disease and Other Degenerative Tissue Effects**

–Degenerative changes in the CV system and lens

–Diseases related to aging and immune system dysfunction

- **Risk of Acute Radiation Syndromes due to Solar Particle Events**

–Prodromal effects (nausea, vomiting, anorexia, and fatigue)

–Skin injury

–Depletion of the blood-forming organs and immune dysfunction

Risks documented in HRP Evidence Books

Assessing cancer risks from space radiation exposure

Exposure of human to gamma/X rays (low-LET) at high dose and high dose rate → Exposure of human to charged particles (High-LET) at low dose and low dose rate

$$R(\text{High LET, LD, LDR}) = \sum \frac{R(\text{Low LET, HD, HDR}) \times Q(\text{LET, Z, E})}{DDREF(\text{LET, Z, E})}$$

(Simplified equation)

Exposure of human cells/animals to gamma/X rays (low-LET) → Exposure of human cells/animals to charged particles (High-LET)

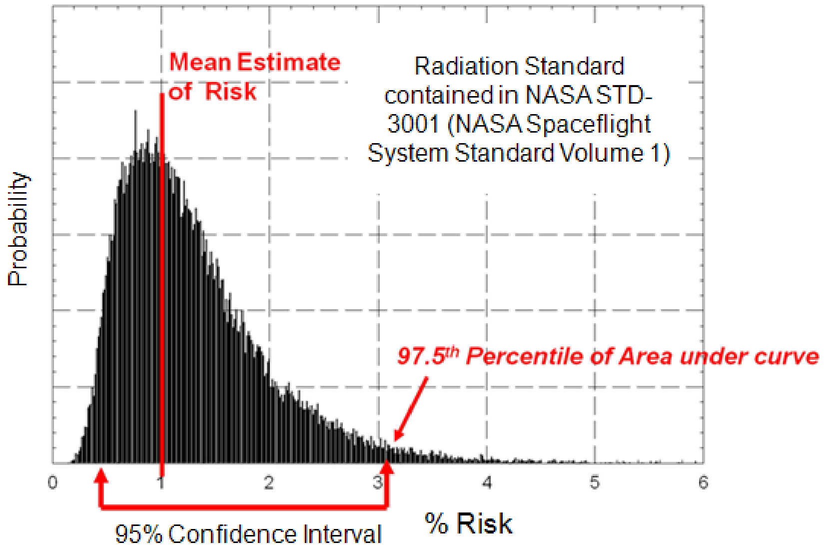
Determine Q(LET, Z, E)
DDREF(LET, Z, E)
from cell/animal studies

Sources of uncertainties in risk assessment

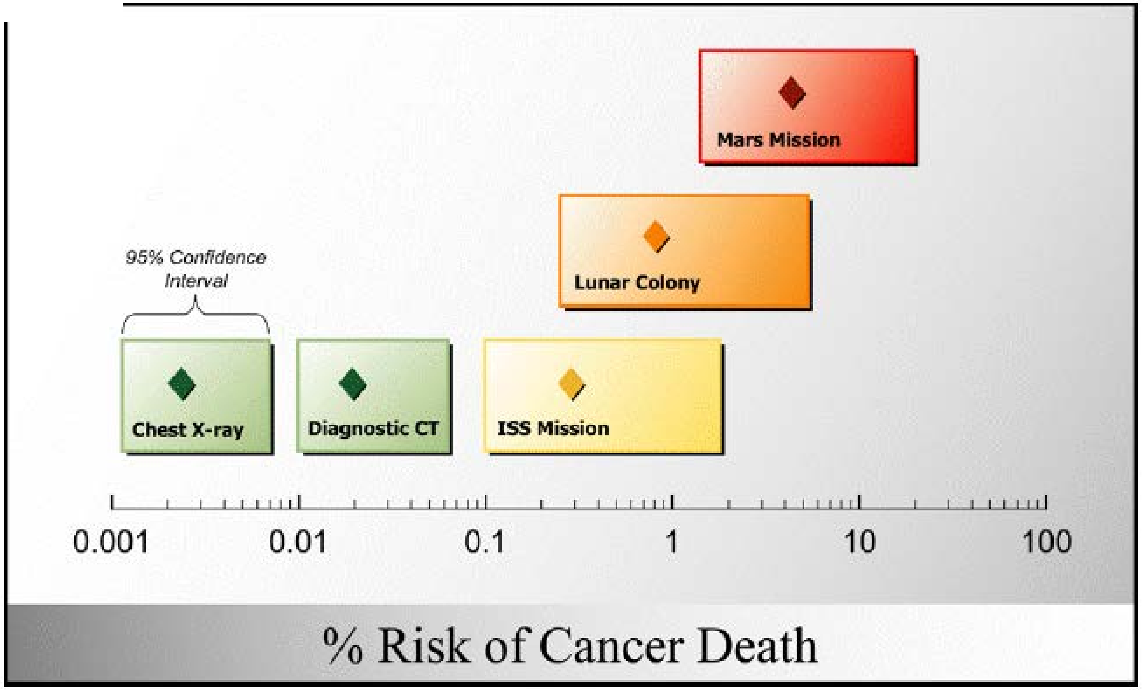
- Uncertainties in determining the qualitative and quantitative differences between the biological damage induced by space radiation compared to X-rays
- Uncertainties in human epidemiological data including statistical, record keeping, dosimetry, and bias resulting from mis-reporting of cancer deaths
- Uncertainties in transferring radio-epidemiology data to other populations, including cancer rates and survival data in the population of interest for space applications
- Uncertainties in transferring radio-epidemiology data to other radiation types and dose rates of interest to space applications
- Uncertainties in the shape of the dose-response curve at low doses (i.e. linear, linear quadratic) and the possibility of dose thresholds
- Uncertainties associated with extrapolation of experimental data from animals to humans
- Uncertainties associated with individual radiation sensitivity factors, including age, genetic, epigenetic, dietary, and "healthy worker" effects
- Uncertainties in space radiation environmental models, transport codes, geometry models, and dosimetry methods
- Uncertainties associated with predicting SPE occurrence, energy spectrum, and magnitude
- Possible inter-dependence of any of the uncertainties mentioned above

From NASA HRP Evidence Book

Cancer risk projection



Uncertainties in risk projection for terrestrial and space exposures (From Durante and Cucinotta 2008; NASA HRP Evidence Book 2016)



Cancer research focus

- Reducing the uncertainties in risk assessment
- Development of biomedical countermeasures
- Availability of simulated GCR and low dose rate neutron capabilities

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	100	*Polyethylene degrader to*		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	100	*Polyethylene degrader to*		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				*500.0*

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	20.0	0.43	2.59	30.4
^{1}H	23.3	0.56	2.29	6.7
^{1}H	27.2	0.75	2.02	7.4
^{1}H	31.7	0.98	1.79	8.0
^{1}H	37.0	1.30	1.58	8.7
^{1}H	43.2	1.72	1.39	9.3
^{1}H	50.3	2.26	1.23	10.0
^{1}H	58.7	2.99	1.09	10.6
^{1}H	68.5	3.95	0.97	11.1
^{1}H	79.9	5.20	0.86	11.2
^{1}H	100.0	7.76	0.73	**27.2**

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{4}He	20.0	0.43	10.34	**11.0**
^{4}He	23.3	0.57	9.14	**2.1**
^{4}He	27.2	0.75	8.06	**2.2**
^{4}He	31.7	0.99	7.12	**2.3**
^{4}He	37.0	1.31	6.29	**2.5**
^{4}He	43.2	1.73	5.56	**2.6**
^{4}He	50.3	2.28	4.92	**2.7**
^{4}He	58.7	3.01	4.36	**2.7**
^{4}He	68.5	3.97	3.86	**2.7**
^{4}He	79.9	5.23	3.43	**2.7**
^{4}He	100.0	7.81	2.90	**6.1**

GCR is simulated at NSRL with a combination of 33 different particle types and energies

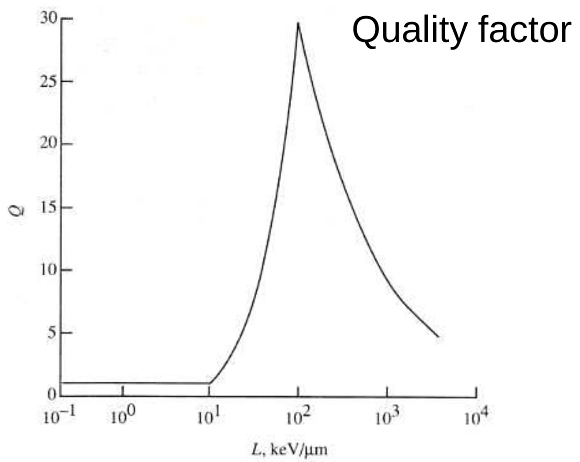
Low dose rate neutron facility at CSU

Animal Irradiation at Colorado State
Cf-252 Neutrons at 1 mGy/day

2,200 Mice for up to 400 days

Radiation quality effects

Assessing high-LET risks from known low-LET radiation risks through mostly animal studies



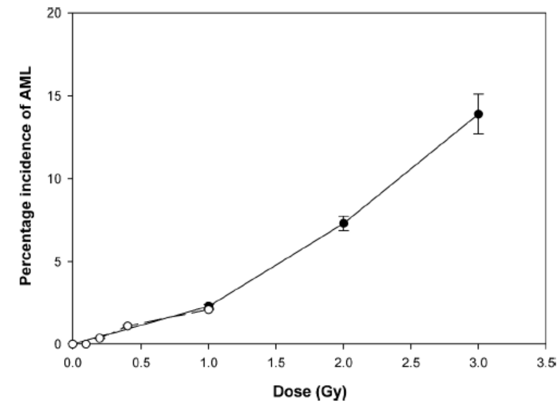


FIG. 1. Percentage incidence of AML (±SE) as a function of dose after exposure to ^{137}Cs γ rays (solid circles) or 1 GeV/nucleon ^{56}Fe ions (open circles).

- Previously, a single quality factor was used for all cancers.
- Studies have shown that the effectiveness of high-LET radiation can be cancer-type specific.
- Quality factor can now be determined with simulated GCR.

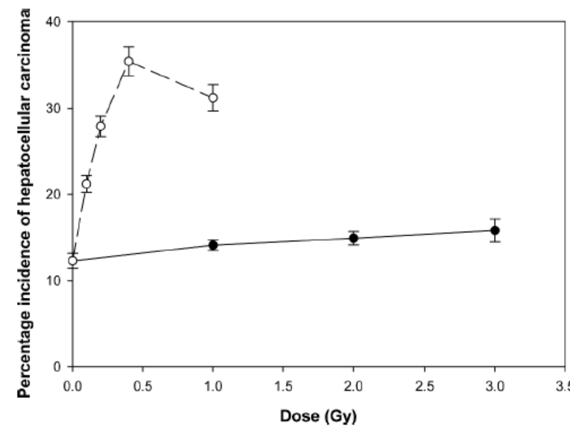
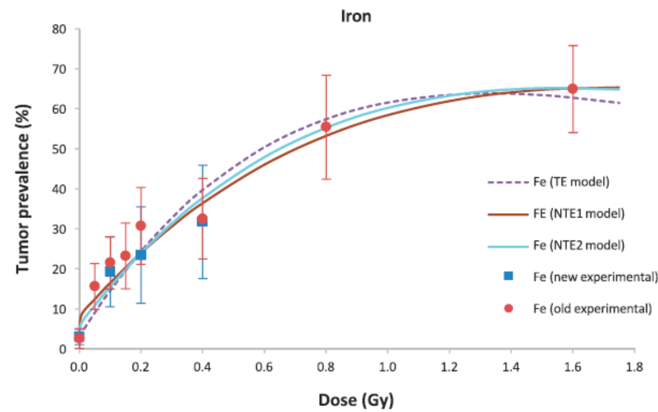


FIG. 2. Percentage incidence of hepatocellular carcinoma as a function of dose after exposure to ^{137}Cs γ rays (solid circles) or 1 GeV/nucleon ^{56}Fe ions (open circles).

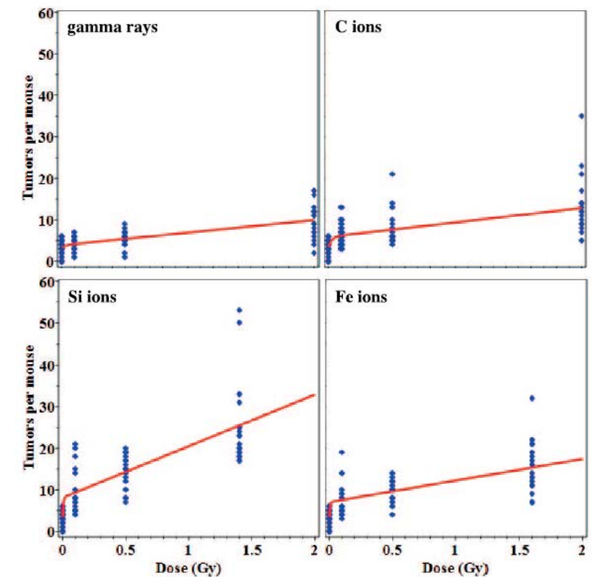
Weil et al. 2009

Dose and dose rate effects

- A number of studies have shown hypersensitivity for high-LET radiation at low doses.
- The non-targeted effects have been suggested as an explanation for the super-linear dose response, which potentially increase the risk from previously determined values.
- Low dose rate neutron studies are underway.



Chang et al. Rad. Res. 2016



Shuryak et al. Rad. Res. 2017

Age and gender effects

- Cancer rates due to radiation exposure are higher in females not only because of female specific organs.
- The life expectancy today is significantly longer than the Japanese after WWII.
- Published million worker study is inclusive of the gender difference in radiation-induced lung cancers.
- Publications have reported higher radio-sensitivity for older people.

Career dose limits (in Sv) corresponding to 3% excess cancer mortality for 10-year careers as a function of age and sex

	NCRP Report No. 98		*NCRP Report No. 132*	
Age, yr	Male	Female	Male	Female
25	1.5 Sv	1.0 Sv	0.7 Sv	0.4 Sv
35	2.5	1.75	1.0	0.6
45	3.2	2.5	1.5	0.9
55	4.0	3.0	3.0	1.7

Schuster *et al. BMC Geriatrics* (2018) 18:105
https://doi.org/10.1186/s12877-018-0799-y

BMC Geriatrics

RESEARCH ARTICLE Open Access

Rate of individuals with clearly increased radiosensitivity rise with age both in healthy individuals and in cancer patients

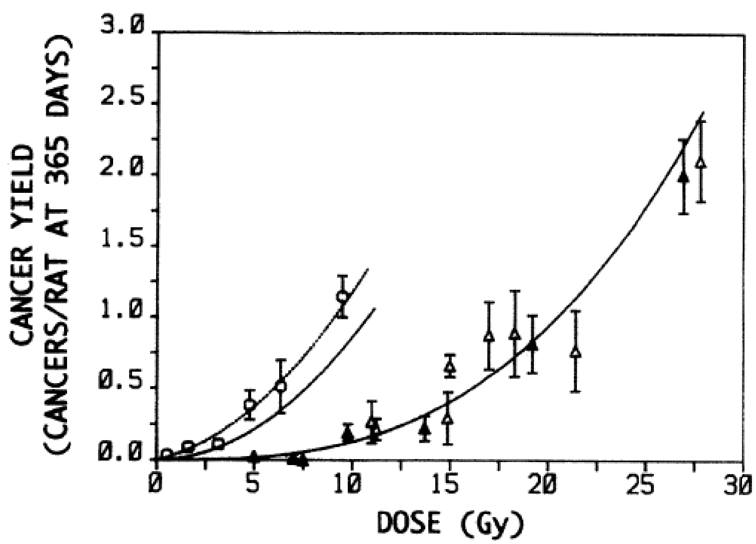
Barbara Schuster[1], Anna Ellmann[1], Theresa Mayo[1], Judith Auer[1], Matthias Haas[2], Markus Hecht[1], Rainer Fietkau[1] and Luitpold V. Distel[1*]

Tumor grade/progression/metastasis

- High-LET radiation may induce tumors of different malignancy and latency.
- Proton radiation has been shown to induce cancer progression.
- Simulated microgravity has been reported to increase tumor growth and metastasis.
- Psychological stress experienced in space can potentially affect cancer risks.

Skin cancer

- A number of cohort studies have reported elevated skin cancers among airline pilots. UV exposures during recreational activities are insufficient to explain the increased skin cancer rate.
- Several astronauts have died of melanoma.
- Animal studies have shown potential high RBE values for skin cancer for high-LET radiation



Cancer yield in rat skin exposed to electron radiation or argon ions. (Burns et al. Rad. Res. 1993)

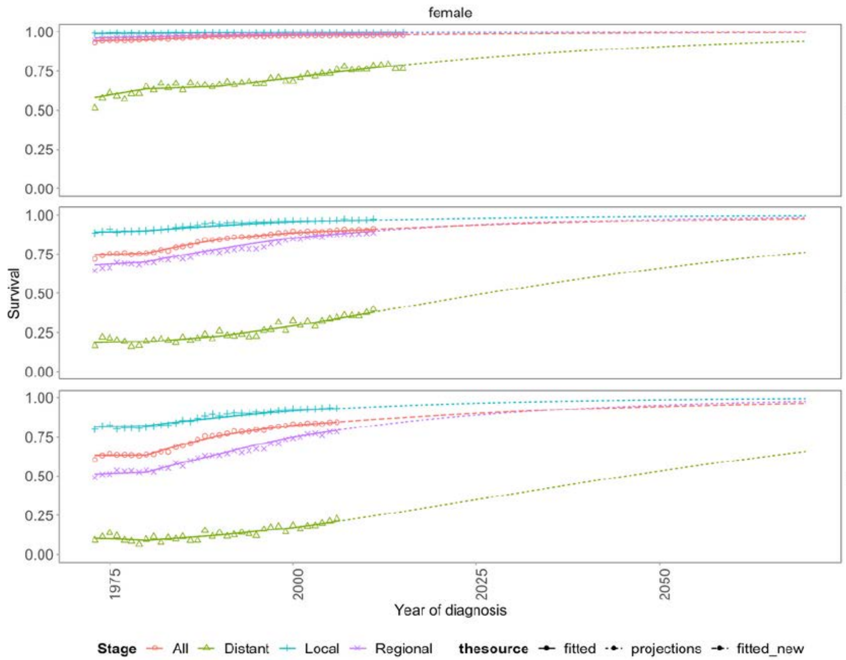
Cause of death in astronauts

Primary Cause of Death among NASA Astronauts as of 12/31/2019			
	Flyer	**Non-Flyer**	**Total**
Cancer	**19**	**2**	**21**
AML	1		1
Breast	1		1
Colon	1		1
Gallbladder	1		1
Glioblastoma		1	1
Lung Cancer	1		1
Lymphoma of the Brain	1		1
Melanoma	3		3
Mesothelioma	1		1
Myelodysplastic Syndrome	1		1
Nasopharyngeal	1		1
Pancreas	2		2
Prostate	5		5
Unknown Cancer (Presumed GI)		1	1
CVD/Stroke	**10**	**3**	**13**
Accident	**6**	**3**	**9**
Occupational Accident	**12**	**6**	**18**
Illness/Other	**7**	**1**	**8**
Unknown	**1**		**1**
Grand Total	**56**	**14**	**70**

Summary of recent findings

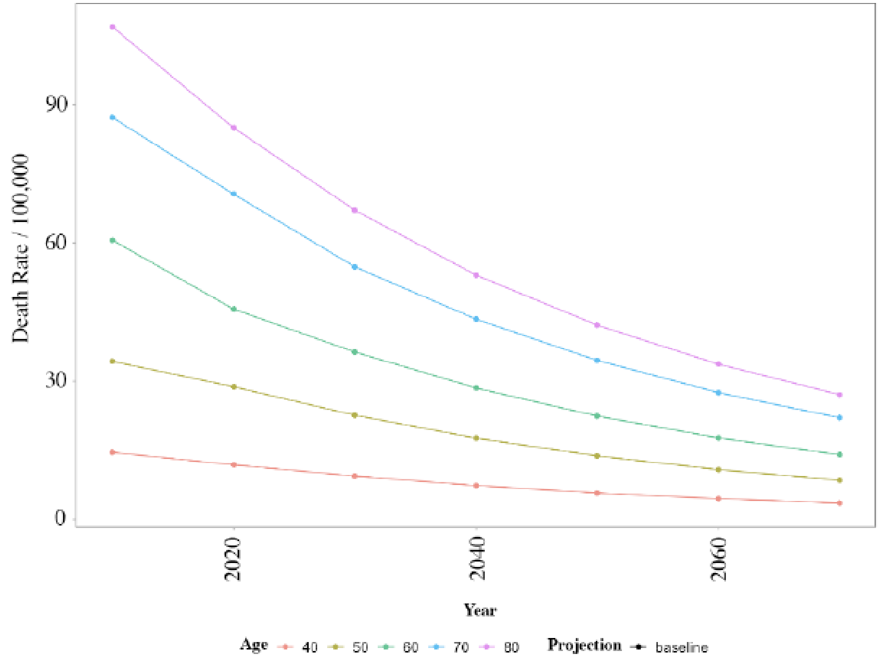
- Several findings, including hypersensitivity at low doses of high-LET radiation and effects of other spaceflight factors on tumor progression, can potentially increase the mean value of the cancer risk.
- The quality factor can be different for different cancer types. GCR simulation provides a unique opportunity to experimentally determine the quality factor for GCR exposure and for validating the risk assessment tools based on model calculations.
- A number of other spaceflight factors, including microgravity and immune dysfunction, can potentially affect cancer initiation, promotion and progression.
- Analysis of astronauts' cancer incidence and cancer mortality data is underway.

Future direction considerations



Historical and projected female 1, 5 and 10-year survival rates by stages of breast cancer

Baseline mortality projections for female breast cancer patients



Potomac Institute Report 2019

Future directions – Potomac Report

- Advanced technologies in early diagnosis of cancer will increase (decrease) the survival (death) rate. Biomarker development for early detections of cancer should be considered.
  - Molecular profiles, omics
- Advancement in treatment of cancer will increase (decrease) the survival (death) rate. Future technologies including molecular therapeutics and drug delivery should be considered.
  - CRISPR/Cas9
  - Synthetic biology
- However, the absolute number of cancer deaths has increased in recent years due to the aging population, which raises the question of updating the radiation protection principles for space travel.
  - Cancer incidence rate instead of mortality rate?

Future directions

- Continue investigations of radiation risks and development of countermeasures.
  - Humanized animal models
  - Tissue on a chip
  - Space vivarium on Gateway and Lunar surface
- Future risk assessment and countermeasures should be individually based.