NASA Space Radiation Program
Integrative Risk Model Toolkit

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The Space Radiation Problem

- Space radiation is comprised of high-energy protons and heavy ions (HZE’s) and secondary radiation protons, produced in shielding (neutrons, heavy ions)

**High Linear Energy Transfer (LET)**

- Unique damage to biomolecules, cells, and tissues occurs from HZE ions produce qualitatively distinct damage from X-rays and gamma-rays on Earth

- No human data to estimate risk from heavy ions and the uncertainties in risk estimates
  - Radiation quality effects
  - Dose-rate effects
  - Human epidemiology data
  - Microgravity influence
  - Radiation environment
  - Transport models
NASA Space Radiation Risk Tools

- **NSCR 2012: NASA Space Cancer Risk 2012**
  Projection of cancer risk from exposure to space radiation

- **ARRBOD: Acute Radiation Risk and BRYNTRN (Baryon Transport) Organ Dose**
  Organ dose projection and acute radiation risk calculation from exposure to SPE (solar particle event)

- **GERMcode: GCR (Galactic Cosmic Ray) Event-based Risk Model (GERM) code**
  Basic physical and biophysical properties for an ion beam, and biophysical and radiobiological properties for a beam transport to the target in the NSRL (NASA Space Radiation Laboratory) beam line

- **RITRACKS: Relativistic Ion TRACKS**
  Simulation of heavy ion and $\delta$-ray track structure, radiation chemistry, DNA structure and DNA damage at the molecular scale

- **NASARTI: NASA Radiation Track Image**
  Modeling of the effects of space radiation on human cells and tissue by incorporating a physical model of tracks, cell nucleus, and DNA damage foci with image segmentation for the automated count

- **HemoDose: Hemocyte Dose**
  Retrospective dose estimation by using multi-type blood cell counts
THE OVERVIEW (HIGHLIGHT) OF TOOLS
NSC: an integration of major scientific developments in multiple science areas as a power analysis tool

**Badhwar-O’Neill 2011 (BON11) GCR Model**
- Developed at JSC provides a self-consistent solution to Fokker-Plank equation for particle transport in the heliosphere
- Distinct modulation of protons and high charge (Z>1) elements
- The most accurate GCR model in numerous comparisons: BON11 root-mean-square errors <10% for all elements

**Radiation Quality Factors (QFs)**
- New QFs based on microscopic energy deposition, the research results on particle cancer risks
- Supported by NRC and approved by NASA, and NASA QF being considered by ICRP for international use

**Dose-Rate Modifiers**
- The Dose and Dose-rate Reduction Effectiveness Factor (DDREF) for chronic exposure risk estimates (GCR or SPE): The DDREF has a larger impact for GCR risk estimates compared to shielding of more than 1-m of PE or water
- Extensive Bayesian analysis for an uncertainty distribution from the DDREF to improve the accuracy of risk estimates

**Integration to User Friendly Web Server**
- Web server for NSCR is at USRA using 96-node Beowulf cluster
- The NSCR server provides users with several thousand analysis options

**Approval and Operational Use**
- The National Research Council (NRC) reviewed NSCR in 2012
- Responses to NRC report completed, model approved by NASA Chief Health and Medical Officer in August 2012
- All NASA software requirements met with independent code verification
- NSCR-2012 v1.0 was released October 2012: Used for ISS Medical Operations and Exploration Studies
Application of NSCR to Medical Exposures
- CT-scans with significant doses have 1-excess cancer per 10,000 to 20,000 procedures
- Medical exposures evaluation for cancer risks for different ages, gender and smoking status from X-rays and CT-scans
- Other codes do not consider uncertainties and estimate only for limited populations

Application of NSCR to Space Exploration
- Analysis of the RAD experiment on the Curiosity rover (Zeitlin et al., Science May 31, 2013)
- Attenuation of GCR and SPE by Martian atmosphere, soils, and rover (Kim et al., JGR-Planets, June 17, 2014)
- Shielding effectiveness & electronics damage for protection (Cucinotta et al., PLOS one, Oct. 15, 2013)

Award
RITRACKS: a Monte-Carlo simulation code to provide a detailed model of the interaction between ionizing radiation and biological matter

**Chromatin Fiber Model**
- Using crystalline structure of nucleosomes, the DNA atomic structure, and the histone proteins

**Electron Track Simulation**
- Various radiolytic species by diffusion and chemical reaction with the DNA molecule for possible DNA damage, formation of double-strand breaks, chromosome aberrations and eventually biological consequences

**DNA Damage Simulations in the DNA Bases**
- Modeling the ionization of each electron of the molecule

**DNA Damage Simulation for the Formation of DSBs**
- Building a chromatin fiber from nucleosome units and linker DNA

**DNA Damage/γH2AX foci Studies**
- Calculating DSBs by low- and high-LET radiation

**Radiation Chemistry**
- Simulating diffusion and chemical reactions in a 2.5 keV electron track

**Tissue Models constructed from Voronoi Tessellation**
- Currently not included in RITRACKS, but to be implemented for future multi-scale models

**Award**
ARRBOD: an integration of NASA models of SPE environments and organ dose evaluation into tool for mission risk assessments using predictive codes

**Baryon Transport (BRYNTRN) Code**
- Extensive input preparation requirements handled easily, correctly, and friendly

**Organ Dose Projection**
- An output data processing module for the response model of organ dose projection

**Prodromal Risks using Non-linear Kinetics of Bone Marrow Stem Cells**
- Acute radiation response for symptoms, severity and the dose summary

**Blood System Responses**
- Modeling of hematopoietic responses and simulation of dynamics of granulocyte, lymphocyte, leukocyte, and platelet

**Value to NASA Mission**
- Support of mission/spacecraft design and operational planning to manage radiation risks in space missions
- NASA trade studies of mission scenarios, shielding materials, masses and topologies for protection of astronauts from space radiation
- Proper shielding solutions to avoid ARR symptoms and to stay within the current NASA Dose limits
- Quantified evaluation of dose and ARR severity to guide alternative solutions for the determined objectives set by mission planners
- ARRBOD fulfills National Research Council (NRC) Recommendations from 2008 on development of probabilistic approach to SPE’s, *Managing Space Radiation Risk in the New Era of Space Exploration*

**Award**
- Competed for 2010 JSC Exceptional Software Awards
- ARRBOD v1.0 and v2.0 are NASA milestones for the Office of Management and Budget (OMB) in 2012
GERMcode: a stochastic simulation tool using track structure and nuclear interactions for the description and integration of physical and biophysical events from mono-energetic ions; and a stochastic Monte-Carlo based model of radiation transport in spacecraft shielding and tissue with the quantum multiple scattering model of heavy ion fragmentation (QMSFRG) and the energy loss processes.

**GERMcode Features - Physics/Chemistry**
- Physical description of the space radiation environment
- Stochastic transport of particles in the NSRL beam-line
- Stochastic transport of ions in spacecraft and tissue shielding
- Models of nuclear fragmentation and particle energy loss
- Amorphous models of radiation tracks and frequency distributions of energy in DNA volumes
- Biophysical response models

**Application of GERMcode at NSRL**
- The scientists participating in NSRL experiments obtain the data needed for the interpretation of their experiments
- Ability to model the beam line, the shielding of samples and sample holders
- Estimate of basic physical and biophysical outputs of the designed experiments

**Application of GERMcode to Space Exploration**
- Assessment of radiation effect on food and pharmaceuticals during a Mars mission (Kim et al., THREE, Jan. 2015)
- GCR reference field design for radiobiological research using ground based accelerators (Kim et al., COSPAR 2014)
THE OVERALL I/O SEQUENCES
NASA Space Cancer Risk (NSCR) 2012

Processor 0  Processor 1  Processor 2  Processor 3

BRYN.f  BRYN.f  BRYN.f  BRYN.f

Sum.f  Sum.f  Sum.f

Organ dose

Post-results

Env. Database

Post.c++

Weighted fluence

NASA Eff. dose

MC-results

Demographic Database

MC-post.f

%REID/%REIC

%REID contributions

%REID/%REIC vs age

Next cancer run?

Start over?

Start

Y

N

End

Y

N
Acute Radiation Risk and BRYNTRN Organ Dose (ARRBOD) v2.0

Start

BRYNTRN+SUMDOSE SPE exposure

Organ dose and LET distribution

Gender

Male

Male (EVA & Spacecraft)

BFO \text{male} (EVA & Spacecraft)

Simulation time?

Blood Cell Kinetics

Blood Cell Kinetics

Lymphocytes depression

Granulocytes modulation

Fatigue and weakness

UGC distress

Female

Female (EVA & Spacecraft)

Simulation time?

Blood Cell Kinetics

Blood Cell Kinetics

Lymphocytes depression

Granulocytes modulation

Fatigue and weakness

UGC distress

Dose data summary

Blood Cell Kinetics

Blood Cell Kinetics

Lymphocytes depression

Granulocytes modulation

Fatigue and weakness

UGC distress

Prodromal Syndromes

Prodromal Syndromes

Lymphocytes depression

Granulocytes modulation

Fatigue and weakness

UGC distress

Start over?

Print, View, or Save

Start

ARR Web Tools for radiation beam exposure

Blood Cell Kinetics

Blood Cell Kinetics

Lymphocytes depression

Granulocytes modulation

Fatigue and weakness

UGC distress

Simulation time?

BFO_{total} > 532.6 \text{ mGy-Eq}

Acute

BFO_{total} dose

t_{simulation} Graph/Table

BFO dose rate

t_{exposure} \rightarrow t_{simulation} Graph/Table

BFO dose rate

t_{exposure} \rightarrow t_{simulation} Graph/Table

BFO_{total} dose

t_{simulation} Graph/Table

BFO dose rate

t_{exposure} \rightarrow t_{simulation} Graph/Table

BFO dose rate

t_{exposure} \rightarrow t_{simulation} Graph/Table

Print, View, or Save

End
RITRACKS v3.0

Input parameters
Radiation: Type of particle, Energy, Fluence
Medium: Irradiated surface, Length

Preparation
Preparation of simulation
Cross sections: Electrons, Ions, Photons, Neutrons, DNA
Chemistry: Reaction rate constants and radii

Parallel processing
- Create directory 1
- Execute calculation (random numbers sequence 1) on CPU 1
- Create directory 2
- Execute calculation (random numbers sequence 2) on CPU 2
- Create directory N
- Execute calculation (random numbers sequence N) on CPU N

Calculations
Initialize particles for transport

Post-simulation processing
Particles left? Y
- Particles transport routines
- Creation of secondary particles

N
Data collection and averaging

Output
Radiation track structure
- Radiolytic species
- Energy deposition events

Dosimetry
- Radial dose
- Voxel dose
- Target dose
- Tissue models

DNA damage
- Nuclei (DSBs)
- Direct effect
- Indirect effect
NASA Radiation Track Image (NASARTI) v3.0

Start → Choose model

1. Cell nucleus model and DNA fragmentation
   - Build a cell nucleus:
     - Outline the membrane
     - Use random walks for chromosomes
     - Impose loops and domains
   - Insert particle tracks or X-rays and gamma rays:
     - Randomly distributed tracks
   - Generate DSBs:
     - Count DNA fragments

2. Image processing and segmentation
   - Analyze an image:
     - Threshold pixels
     - Identify objects
     - Colocalize objects
   - Display results graphically:
     - Use OpenGL or TIFF to visualize scientific data
     - Analyze data with spreadsheets or data plots

3. Irradiated Tissue Model
   - Build a cell matrix:
     - Use segmentation algorithm
     - Impose boundary conditions
     - Define a cube of physical space
   - Insert particle tracks or X-rays and gamma rays:
     - Randomly distributed tracks
   - Generate apoptotic cells:
     - Analyze cell death patterns

End

Monte Carlo sampling
http://spaceradiation.usra.edu/irModels/

Integrative Risk Models Toolkit

Download Software
• ARRBOD
• GERMCode
• NASARTI
• RITRACKS
• HemoDose

Online Tools and Models
• ARRBOD 2.0 Web Server
• NSCR2012 V1.0 Web Server
• HemoDose Web Tools

To request a username and password to download the software or to access the online tools, please contact Dale Ward ward@dsls.usra.edu.